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*By*

JOHN KELLOCK ROBERTSON, F R S C

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## Radiology Physics



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X-ray of the painting, *Portrait of a Lady* by Pourbus, made at the Fogg Art Museum, Harvard University, under the Milton Fund.

# Radiology Physics

AN INTRODUCTORY COURSE FOR MEDICAL OR PREMEDICAL  
STUDENTS AND FOR ALL RADIOLOGISTS

By

JOHN KEI LOCK ROBERTSON, F.R.S.C.

*Professor of Physics,  
Queen's University, Kingston, Canada*

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SECOND EDITION SECOND PRINTING

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## PREFACE TO THE SECOND EDITION

The developments in nuclear physics which were announced to the world with dramatic suddenness in August 1945 are of great importance in the field of radiology and have made a second edition of *Radiology Physics* desirable. In carrying out the revision, the author has added new work in atomic physics and at the same time has taken the opportunity to overhaul the whole book, rearranging the order and amplifying where necessary. The elementary character of the book has been maintained, for it is essentially an introduction to a vast field whose importance in biology and in medicine is now fully recognized.

In the preparation of the manuscript the author has consulted freely current literature on nuclear and atomic physics and, in particular, would like to express his indebtedness to *Medical Physics*, edited by Otto Glasser, and to *Lectures in the Physics of Radiotherapy* by M. V. Mayneord, complimentary copies of which were received from the Ontario Institute of Radiotherapy. Acknowledgement is gladly made of helpful suggestions received in conversation with Professor Mayneord, of the Royal Cancer Hospital, London, and with my colleague, Dr. H. M. Cave. A number of new illustrations have been introduced and, for some of them or for permission to use them, my grateful thanks are due Dr. Matthew Luckiesh, Dr. Edith Quimby, Professor Pierre Demers, Professor Serge A. Korff, The Victoreen Instrument Company, Machlett Laboratories, Incorporated, *Radiology* and Dr. J. M. Cork.

The author would like to take this opportunity of expressing his appreciation of helpful comments made by many after the original publication of *Radiology Physics* and, in particular, to thank Dr. Marvin M. D. Williams, of the Mayo Foundation, Rochester, Minn.

Queen's University,  
May, 1948

J. K. R



## PREFACE TO THE FIRST EDITION

With the ever increasing applications of physics in medicine the problem of giving the medical or the premedical student adequate instruction in physics has become one which demands action. To teach in one year the fundamental principles of physics, and at the same time to deal adequately with those applications with which a medical student should be familiar, is well nigh impossible. At Queen's University the problem has been solved and, on the whole, satisfactorily, by giving instruction in two successive years. In the first year, the student is given the usual course in general physics, with the omission of electricity and magnetism. In the second year, lectures and laboratory work in electricity and magnetism lead naturally to a consideration of such topics as x-ray transformers, x-ray tubes, conduction of electricity through gases, radioactivity, nuclear physics, and high frequency currents. RADIOLOGY PHYSICS covers, with some amplification, the work given by the author in the second half of this course.

It is hoped that this book will prove suitable as a text for similar courses elsewhere, especially for those institutions which agree with the Committee on the Teaching of Physics for Premedical Students\* in their opinion "that the American Association of Physics Teachers should go on record as in favour of making the physics prerequisite two years instead of one." RADIOLOGY PHYSICS is also commended to all radiologists and radiological technicians who wish, not a handbook, but a simple explanation of the physical principles underlying the use of their apparatus. Although a knowledge of elementary electricity and magnetism is assumed, the mathematical treatment is reduced to a minimum.

In the preparation of the manuscript, the author has made some use of an earlier book on *X-rays and X-ray Apparatus*, and his thanks are due the President of D. Van Nostrand Company, Inc., for permission to use some of the material in the more recent *Atomic Artillery*. Under each illustration due acknowledgment is made where necessary, but my special thanks are due the Philips' Gloedampenfabrieken, Eindhoven, Holland, the General Electric X-ray Corporation, Dr. J. G. Trump of the Massachusetts Institute of Technology, and Mrs. Edith Qumby and Dr. G. Failla of the Memorial Hospital, New York, for photographs and other material. Acknowledgment

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is also made of the kindness of Mr A C Baldwin, Mr G E. Simons, and Dr J Gross, of the General Electric Corporation, and Mr Victor Hicks of the Westinghouse X-Ray Company

It is a pleasure to thank my wife for her valuable assistance throughout the preparation of the book, and my colleagues Dr B W Sargent, who read part of the manuscript, and Dr H W Harkness, who read the chapters on high voltage With Dr Sargent the author has had many discussions My friend and colleague Dean A L Clark has again provided clerical and other assistance and it is a pleasant duty to express to him my appreciation

J. K. R.

QUEEN'S UNIVERSITY,  
KINGSTON, CANADA  
October, 1940

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# CHAPTER I

## ALTERNATING CURRENTS

The aim of this text is to present in a systematic way the fundamental physical principles utilized in the field of radiology. It is assumed that the reader has had a general course in physics such as is given in the first year of liberal arts or to premedical students, but the author does not hesitate to review and to amplify important parts of the elementary course. For example, at the outset the student is asked to recall a few principles in electricity and magnetism, that branch of physics whose applications abound in radiology.

**1 Electromagnetism** — All students are familiar with the fact that when a bar magnet is placed beneath a sheet of paper on which iron filings are sprinkled, the filings arrange themselves along regular lines. This simple experiment indicates that in the region around the magnet there is a *magnetic field of force*. To visualize this field we say that it is traversed by magnetic lines of force, the actual number of lines being so chosen that at any particular place, the *intensity* or strength of the magnetic field is equal to the number of lines passing through an area of 1 sq cm, the area being at right angles to the direction of the lines. A field of unit intensity, it will be recalled, is equal to 1 dyne per unit pole and is called 1 *oersted*.

These lines of force are closed curves which leave the north pole of the magnet and enter the south, constituting what is called a *magnetic flux* through the magnet. Indeed, whenever magnetic lines pass through any region, we speak of a magnetic flux through that region.

Elementary experiments with electric currents prove that a magnetic field surrounds a wire carrying a current and show that if the wire is bent into a solenoidal coil, as in Fig. 1, one end of the solenoid is a north pole, the other a south. Moreover, if the air inside the solenoid is replaced by a core of soft

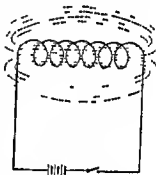


FIG. 1. Lines of Force are linked with a solenoidal coil carrying a current.

iron the iron becomes strongly magnetized under the influence of the magnetic field due to the current and a powerful electromagnet may be created. We can have magnetic fields therefore subject to the control of an electric circuit. When the circuit is closed the magnetic lines are said to be *linked* with the turns of the circuit the number of *linkages* being equal to the product of the total magnetic flux times the number of turns of the circuit with which they are linked. When the circuit is broken the lines disappear, with a consequent change in the number of linkages.

**2 Electromagnetic Induction** — Suppose a wire  $AB$ , Fig 2 which forms part of a simple closed circuit containing a galvanometer  $G$  but no battery, is free to be moved between the poles of an electromagnet whose circuit is closed. If  $AB$  is moved from position I across the lines of force to position II (indicated by  $AB$ ) a momentary current is indicated by the galvanometer. If the wire  $AB$  is moved back again, a momentary current in the opposite direction is recorded. In general, it is found that as long as the wire is moving with respect to the lines of force a current is developed. This and many other similar experiments prove that *whenever a portion of any circuit is moving with respect to magnetic lines of force an induced electromotive force (E M F) is developed and if the circuit is closed, an induced current results.*

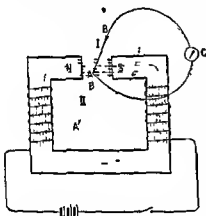


FIG 2 When the wire  $AB$  is moved across the magnetic field an induced electromotive force is developed in the wire

This is the very important principle of electromagnetic induction discovered in 1832 by Faraday in England and simultaneously by Henry in the United States.

The principle may be stated in another and possibly more useful way. When the movable wire  $AB$  is in position I there are no lines of force linked with the galvanometer circuit, but when it is in position II all the lines are linked or interlocked with that circuit. Frequently, then we state that an induced E M F is developed in a circuit wherever there is any *change* in the number of lines linked with it. If for example the wire is left in position  $AB$  and the electromagnet circuit (the *primary* circuit) is *broken*, there is a momentary induced current in the movable wire circuit (the *secondary*). Again, when the primary circuit is *made*, a momentary induced current results.

in the secondary In this experiment, the secondary circuit is not moved, but the magnetic lines appear on make of the primary, disappear on break, and so on both make and break there is relative motion of lines and a portion of a circuit Or, stating it the other way, on *break* of the primary, there is a decrease in the number of lines linked with the secondary, on *make*, an increase — in both a change, and hence an induced E M F is developed

The magnitude of the induced E M F is found by experiment to depend on the *rate* at which the lines are cut or on the rate at which the number of linkages is changing Large E M F may be obtained, therefore, when numerous electric conductors rapidly cut the lines of strong magnetic fields, or when such fields are linked and “unlinked” with many turns of an electric circuit This, in fact, is the basic principle utilized in dynamos, in transformers and in induction coils

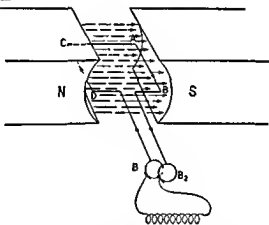


FIG. 3 A simple arrangement to generate an alternating current

move up, thus cutting lines in the opposite direction, and the direction of the induced  $\mathcal{E}$  and of the resulting current reverses. At the same time the wire  $CD$  reverses its direction from up to down, and in it, too, the induced  $\mathcal{E}$  changes direction. It follows, therefore, that with this simple arrangement, for one half of a revolution a current is flowing in one direction, for the other half, in the opposite.

Not only, however, is there a reversal of current (or, if you like, of polarity between the brushes  $B_1$  and  $B_2$ ) but the *strength* of the current is continually changing. This will be evident if it is realized that when the wire  $AB$  is passing through its highest position and the wire  $CD$  through its lowest, each wire is moving parallel to the magnetic lines and hence for a short interval of time there is no cutting and, therefore, no induced voltage and no current. As  $AB$  goes down (and  $CD$  up) the lines are cut more and more quickly until after one quarter of a revolution both  $AB$  and  $CD$  are moving directly at right angles to the lines. At this instant, therefore, the magnetic lines are cut at the fastest rate and the highest induced voltage results. For the next quarter of a revolution, the lines are cut less and less quickly until  $AB$  reaches the bottom ( $CD$  the top) and once more, for a brief moment, each wire is moving parallel to the lines, and the voltage has dropped to zero again. Evidently, then, during one complete revolution, the current in the circuit will gradually rise in one direction to a maximum value, drop until it is zero, from which it gradually climbs to a maximum in the opposite direction, again falling to zero. If the loop is rotated at steady speed and in a uniform magnetic field, the manner in which the current changes with time is represented graphically in Fig. 4.

A current of this type is an *alternating* one (A.C.) as well as *sinusoidal*. Obviously a sinusoidal current is characterized by (1) changing polarity and (2) gradual "smooth" changes in intensity. (See also section 81.)

It is well to note that while a sinusoidal current is always A.C., it is possible to have alternating currents which are not sinusoidal.

Two or three important terms should be noted.

A *cycle* refers to the complete change from zero to a maximum in one direction, down through zero to a maximum in the other direction and back again to zero. In Fig. 4,  $OA$  represents a cycle.

The *frequency* of A.C. is the number of cycles per second. Most householders on the American continent are supplied with A.C. at 110 volts, with a frequency of 60 cycles per second, although as low as 25 is sometimes used.

Neither this voltage nor this frequency could be generated with a simple machine of the type illustrated. In the practical A.C. generators or dynamos or alternators found in power houses, the desired frequency and voltage are

obtained by using several sets of magnet poles, alternately north and south, and many loops of wire. The fundamental principles utilized, however, are the same as those we have been discussing and the current supplied by such generators generally approximates fairly closely to the sinusoidal.

In direct current (D C) generators, it is important to realize that the same principles are utilized and that an alternating E M F is developed in the rotating loops or moving conductors. By the use of commutator plates, this alternating current is *rectified* and direct current flows in the external circuit.

**4. Strength of A C** — When alternating currents are used in the laboratory, an A C ammeter placed in the circuit indicates a definite current of so many amperes. Actually we know that the current is varying in the manner represented by Fig 4, being sometimes in one direction, sometimes in another, with magnitude constantly changing. What, then, does the instrument record? To understand the answer to that question, it is necessary to

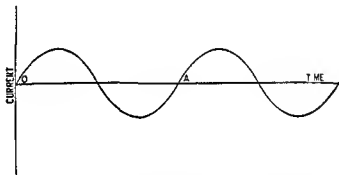


FIG 4 Graphical representation of a simple alternating current

know that, by agreement an alternating current has a value or strength equal to that of a direct current which produces the same heat in a given resistance, in the same time. If for example, in a certain time an alternating current in a coil of wire develops the same heat as a direct current of 2 amperes, the alternating current has a strength of 2 amperes. Sometimes the strength is said to be so many *virtual* amperes, but more often the qualifying word is dropped.

The common D C ammeter of the moving coil type cannot be used to measure alternating current, because with such a current the coil is acted on by rapid impulses tending to rotate it, first in one direction, then in the opposite, and no movement except a possible quivering of the pointer is observed. In a

hot wire instrument, however, the movement of the pointer depends on the change in length and tension of a wire heated by a current and this is independent of its direction. Such an instrument, therefore, can be used for measuring both A C and D C. It is, of course, not the only type.

**5 Meaning of R M S** — The student will recall that the amount of heat developed in a conductor in a given time, depends on the square of the current, or that the power dissipated in a conductor of resistance  $R$  is  $I^2 R$  watts, where  $I$  is the current in amperes and  $R$  the resistance in ohms. With this in mind it should not be difficult to see that, when alternating current is used, the equivalent direct current is equal to the square root of the average of the squares of successive values, if a complete cycle is subdivided into a large number of intervals. For this reason, the strength of an alternating current or the number of virtual amperes is sometimes referred to as the Root-Mean-Square or R M S value. The same expression may be applied to a similar average of any quantity varying according to the same law as is represented by Fig. 4. Alternating voltmeters, for example, record the R M S value of the alternating E M F.

With a little knowledge of calculus it is not difficult to prove that

$$\text{R M S value} = \frac{\text{maximum value}}{\sqrt{2}}$$

$$\text{or} \quad = 0.707 \text{ maximum value.}$$

Thus, if an A C ammeter records 7.07 amperes, we know that the actual current changes from 0 to 10 amperes in each direction.

**6 Inductive and Noninductive Circuits** — Suppose a coil of wire is wound around an iron core, as in any ordinary electromagnet, and that it is supplied with direct current. *Before* the circuit is closed, the magnetic field is weak or absent altogether and the number of magnetic lines linked with the circuit is negligibly small. After the circuit is closed, however, a strong magnetic field exists with a corresponding large number of linkages. *Therefore, during the time immediately following the closing of the circuit*, there is a big change in the number of linkages. Consequently while the change is taking place, an induced E M F, called an *E M F of inductance*, is developed in the coil of the electromagnet.

Now by Lenz's Law any induced E M F is in a direction opposing the change which gives rise to it. This E M F of inductance, therefore, is in a direction opposite to the original applied voltage, and so immediately after the

## INDUCTIVE AND NONINDUCTIVE CIRCUITS

closing of the circuit, the actual current has a value given by

$$\text{current} = \frac{\text{E M F of battery} - \text{E M F of inductance}}{\text{resistance of circuit}},$$

or, in symbols  $I = \frac{E - E'}{R}$ , where  $E = \text{E M F of inductance}$

For this reason the electromagnet current does not immediately attain its final steady value (given by  $I = \frac{E}{R}$ ) but rises somewhat as shown in Fig. 5. Ultimately the number of linkages becomes constant, there is no opposing induced E M F and the current has a constant value.

If the electromagnet circuit is *broken*, the lines of force disappear and, if the break is made quickly enough, a large E M F of inductance is developed in the same direction as the original applied E M F. Its magnitude may be many times greater than that of the original E M F, so great, indeed, that a spark jumps the gap where the break is made. This spark may be accompanied by or followed by an arc between the separated metal parts of the breaking switch, an arc which must sometimes be suppressed by the use of special circuit breakers or magnetic blow-outs.

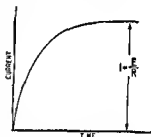


FIG. 5 The rise of a direct current in an inductive circuit

The effect of inductance may be illustrated in a simple manner by the use of an ordinary dry cell and an electromagnet (or primary of a transformer) of low resistance. If the terminals of the cell are short circuited by a piece of copper wire and the circuit suddenly broken, no more than an infinitesimal spark or flash is seen at the place of break. If, however, the cell is connected in series with the electromagnet, on break there is a bright flash. Although the current in the first place is actually greater than in the second, the number of magnetic lines linked with the circuit is so small compared with the number in the second, that the induced E M F on break is not great enough to cause an appreciable spark. With an electromagnet in the circuit, the number of linkages is increased many times and a marked spark occurs when they disappear on break.

This experiment illustrates the difference between a *noninductive* and an *inductive* circuit. In the former, the number of linkages per ampere is so small that the induced E M F on make or on break is negligibly small, in the latter, there is a large number of linkages per ampere with important effects both on make and on break of a direct current. On make there is a delay in



the rise of the current, whereas on break, an E M F, often quite large, is developed. A circuit containing an incandescent lamp is noninductive, one with an electromagnet, inductive.

A circuit has an inductance of 1 henry when the number of linkages per ampere is  $10^9$  or one hundred million\*. For example, if an electromagnet is wrapped with 200 turns of wire and a total flux of 10,000 lines traverses its iron core when the exciting current is 1 ampere, its inductance is

$$\frac{200 \times 10,000}{10^9} \text{ or } \frac{1}{50} \text{ of a henry}$$

**7 Impedance and Inductive Reactance** — When an alternating current flows in an inductive circuit, the magnetic field is constantly changing, and so opposing induced E M F are present at all times. These have an important effect on the magnitude of the average current in the circuit. Let us examine carefully the difference between an inductive and a noninductive circuit in so far as alternating currents are concerned.

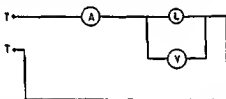


FIG. 6 Simple circuit for measuring resistance for D C or impedance for A C

Suppose a lamp of resistance 440 ohms is joined in series with an ammeter, suitable for either A C or D C, to supply terminals *TT*, as illustrated in

Fig. 6. If the supply voltage is 110 direct, the ammeter reads  $\frac{110}{440}$  or 0.25 ampere. If the supply voltage is 110 alternating (that is, an A C voltmeter placed across the terminals records 110 volts) the ammeter indicates practically the same reading. In other words, Ohm's Law in its simple form holds for both A C and D C when we are dealing with a simple noninductive circuit.

Now replace the lamp by an electromagnet of resistance 50 ohms and inductance 0.3 henry. With direct current, the ammeter records  $\frac{110}{50}$  or 2.2 amperes. With alternating current, the reading is very much less because of

\* One henry is more often defined as the inductance of a circuit such that, when the current is changing at the rate of 1 ampere per second the induced E M F is 1 volt. The two definitions are of course equivalent.

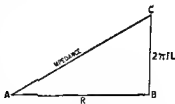
the opposing E M F of inductance. Actually the ammeter records about 0.89 amperes. As far as alternating current is concerned, the electromagnet, therefore, has an effective resistance of  $\frac{110}{0.89}$  or 123.6 ohms. This total resistance to an alternating current is called the *impedance* of the circuit. Its magnitude depends on (1) the true resistance, in this case 50 ohms, and (2) the *inductive reactance*, the name given to the effective resistance arising from the induced E M F.

Since the magnitude of any induced E M F depends on the rate at which the number of linkages is changing, the numerical value of the reactance depends both on the inductance, or the number of linkages per ampere, and on the frequency of the alternating current. Obviously the higher the frequency, the more rapidly the number of linkages is changing. It requires a little more mathematics than is at the disposal of most medical students to prove that the reactance in ohms is equal to  $2\pi fL$ , where  $f$  is the frequency and  $L$  the inductance expressed in henries.

For example, the reactance of the above electromagnet (whose inductance is 0.3 henry) when an alternating current of 60 cycles per second is used is equal to

$$2\pi \times 60 \times 0.3 \text{ or } 113.1 \text{ ohms}$$

It will be noticed that, although  $R$  the true resistance of the electromagnet is 50 ohms and the reactance 113.1 ohms, the impedance is only 123.6 ohms, not the sum of these two numbers. The problem then arises, given the resistance and the reactance, how can we calculate the impedance? The answer is simple, although the proof is not and must be omitted from this text. If we make a right-angle triangle, as in Fig 7,



and let the length of one side represent  $R$  the resistance, the other side  $2\pi fL$ , the reactance, then the impedance is given by the length of the hypotenuse. It follows at once that the impedance  $Z$  is given by the relation

$$Z = \sqrt{R^2 + (2\pi fL)^2},$$

which, for the above electromagnet, gives us,

$$\begin{aligned} Z &= \sqrt{50^2 + (113.1)^2} \\ &= 123.6 \text{ ohms.} \end{aligned}$$

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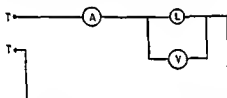


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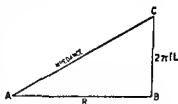


FIG. 7. Triangle showing the magnitude of impedance due to resistance and inductive reactance.

Not long ago a traveler for scientific apparatus was demonstrating a new light designed to work on 110 A C. He was mistakenly told that the D C. supply terminals in a laboratory were A C and on plugging in the lamp, immediately found that it burned out. The impedance of the lamp circuit was much greater than its true resistance, hence when D C. was used, the current was much higher than with A C.

Sometimes the impedance is due almost entirely to the reactance, as in the case of a *choke coil*. This device consists of a coil of wire of low resistance, with an iron core which may be withdrawn from the coil or whose position may be altered in such a way that the value of  $L$  the inductance gradually changes.

In high frequency circuits, which will be discussed in Chapter VIII, the value of the frequency is of the order of a million or a hundred million cycles per second. With such circuits (and we encounter them in radio sets) even a small value of  $L$  may correspond to an appreciable or even a high reactance. For example, if  $L = 1$  microhenry,\* and  $f = 10^6$  cycles per sec., the reactance is  $2\pi$  or 6.28 ohms.

**8 Capacitive Reactance** — When a condenser, such as  $C$ , Fig. 8, is joined to an ordinary battery or to D C. terminals  $TI'$ , the condenser is

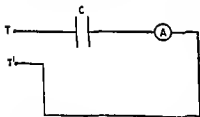


FIG. 8. An ammeter in series with D C. supply and a condenser indicates no current.

charged, but after a momentary initial current, a good condenser acts as an infinite resistance and an ammeter  $A$  placed in the circuit indicates no current. When the condenser is joined to alternating supply terminals, the situation is very different. As the alternating current surges to and fro, the condenser is continually charged and discharged, its plates being alternately positive and negative, negative and positive, and so on. An A C. am-

meter placed in the circuit indicates a current just as if it were in an ordinary lighting circuit.

If the condenser has a capacitance of 1 microfarad and the alternating supply is 110 volts 60 cycles per second, the ammeter actually indicates a current of about 0.415 ampere. The condenser, therefore, is equivalent to an effective resistance, or reactance of  $\frac{110}{0.415}$  or about 265 ohms. This effective resist-

\* The student will scarcely need to be reminded that the prefix *micro* means one millionth or  $10^{-6}$  of the main unit.

ance is called a *capacitive reactance*, to distinguish it from inductive reactance.

The value of the capacitive reactance may be calculated from the expression  $\frac{1}{2\pi fC}$ , where  $C$  is the capacitance of the condenser expressed in farads.\* Taking the above microfarad condenser as an example, we find its reactance to be

$$\frac{1}{2\pi \cdot 60 \cdot 1 \times 10^{-6}} \text{ or } 265 \text{ ohms}$$

If  $f$  is extremely high, as in diathermy or radio circuits, the capacitive reactance is correspondingly small — just the opposite to the reactance of an inductance for such currents. For example, for a 100 million cycle per second frequency, the reactance of a microfarad condenser is

$$\frac{1}{2\pi \cdot 100 \times 10^6 \times 1 \times 10^{-6}} \text{ or } \frac{1}{200\pi}$$

or a small fraction of an ohm.

### 9 Combination of Resistance and Capacitance

—If a noninductive resistance, a tungsten lamp, for example, of resistance  $R$  ohms is inserted in series with a condenser and the two are joined to A C supply terminals, the

impedance of the combination is again found by the use of a right angle triangle. As illustrated in Fig. 9, if one side of the triangle represents  $R$ , and the other, the capacitive reactance  $\frac{1}{2\pi fC}$ , the hypotenuse represents the impedance, or, using a formula, the impedance  $Z$  of a combination of a non-inductive resistance and a condenser is given by

$$Z = \sqrt{R^2 + \frac{1}{(2\pi fC)^2}} \text{ ohms}$$

**10 Resistance, Capacitance, and Inductance** — When the alternating circuit includes resistance, capacitance, and inductance, the impedance of the circuit is given by

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}$$

\* The student will recall that when the potential difference between the plates of a condenser of capacitance 1 farad is equal to 1 volt the charge on either plate is 1 coulomb.

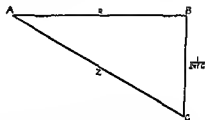


FIG. 9 Triangle showing the magnitude of impedance due to resistance and capacitive reactance

It will be noted that, since in this expression we subtract the two reactances, the impedance may again be found by the use of a right-angle triangle. As before one side represents the value of  $R$ , but the length of the other side is now equal to the *difference* between the inductive and the capacitive reactances. In the special case where the two reactances are exactly equal, they cancel one another and the total impedance reduces to  $R$ . If  $R$  is small, large currents may be obtained with small alternating E M F. We are then dealing with a resonating circuit about which more will be given in Chapter VIII.

**11. Phase Difference** — The student will recall that when a direct current of  $I$  amperes flows under a potential difference of  $V$  volts, the power supplied is  $VI$  watts. It might be expected that the same expression could be applied when alternating currents are used. This, however, is by no means always correct. The power is always *proportional* to the product of  $V$ , the voltage recorded by an A C voltmeter, times  $I$ , the amperage on the A C

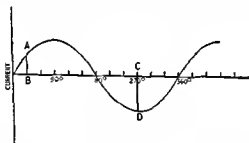


FIG. 10 Graph to illustrate the meaning of phase angle.

ammeter, but it is not always *equal* to this product. To understand why this is so, it is necessary to explain the meaning of *phase*.

In a sinusoidal curve, such as we have shown in Fig. 4 and again in Fig. 10, the magnitude at any instant of the changing current (or any other changing variable that the curve represents) can be calculated from the law  $I = I_m \sin \theta$ , where

$I$  = the magnitude of the current at any instant,

$I_m$  = its maximum value,

and  $\theta$  = an angle whose value steadily increases with the time and changes in one cycle by  $360^\circ$ .

Suppose, for example, that an alternating current has a maximum value of 10 amperes. Then, to obtain the exact shape of the curve which shows how its magnitude changes during one cycle, all that is necessary is to calculate the values of  $10 \sin 0^\circ$ ,  $10 \sin 30^\circ$ ,  $10 \sin 60^\circ$ , etc., and to plot these values against the corresponding angles. Figure 10 illustrates the plot obtained in such a

manner, making use of the numbers given in Table I. Values of  $\theta$  are taken every  $30^\circ$  for convenience, but a still more accurate curve would be obtained by taking angles closer together. Since sine values repeat every  $360^\circ$ , the curve between  $360^\circ$  and  $720^\circ$ , or  $720^\circ$  and  $1080^\circ$ , etc., will be the exact duplicate of that between  $0^\circ$  and  $360^\circ$ .

## TABLE I

$\theta$	$\sin \theta$	$10 \sin \theta$
$0^\circ$	0 00	0
$30^\circ$	0 500	5 00
$60^\circ$	0 866	8 66
$90^\circ$	1 00	10 00
$120^\circ$	0 866	8 66
$150^\circ$	0 500	5 00
$180^\circ$	0 00	0 00
$210^\circ$	-0 500	-5 00
$240^\circ$	-0 866	-8 66
$270^\circ$	-1 00	-10 00
$300^\circ$	-0 866	-8 66
$330^\circ$	-0 500	-5 00
$360^\circ$	0 00	0 00

Now it should be evident that an exact method of describing the particular stage of the cycle which the current (or other variable) has reached at any instant is to give the magnitude of the corresponding angle, or what is called the *phase angle*. Thus at a certain instant when there is a positive current of magnitude  $AB$ , Fig. 10, the phase angle is  $30^\circ$ , or when the current has a negative value  $CD$ , the phase angle is  $270^\circ$ .

Often we are concerned with the phase difference between two different alternating currents at the same instant, or between the phase angle of the alternating voltage and the corresponding current. It might be thought that at any instant the phase angle of the current would be exactly the same as that of the voltage, but, although that is true in some circuits, it is by no means always so. It is possible, for example, to have the state of affairs represented in Fig. 11, where the full line represents the variation in voltage, the dotted line, the corresponding variation in current. It will be noted that when the voltage has a maximum value, the value of the current is zero. In this case, there is a phase difference of  $90^\circ$ , the current lagging behind the voltage by that amount.

Such a phase difference actually exists when we are dealing with an inductance of negligible resistance. If the resistance  $R$  cannot be neglected the phase difference between current and voltage (for an inductive resistance) is



given by the angle  $CAB$  in Fig 7. Calling this angle  $\alpha$ , we see at once that its value may be found from the simple relation

$$\cos \alpha = \frac{AB}{AC} = \frac{\text{resistance}}{\text{impedance}}.$$

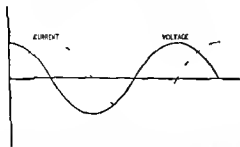


FIG 11 Graphs showing voltage  $90^\circ$  in phase ahead of current

Thus in the example worked out on page 9, we find the amount the current lags behind the voltage by evaluating  $\alpha$ , where

$$\cos \alpha = \frac{50}{123.6}.$$

Hence, phase angle  $= 66^\circ 8'$

*In a noninductive circuit, such as one containing an ordinary incandescent lamp, the reactance is negligible, the current and the voltage are in exact step, and there is no difference in phase*

✓ **12 Power Factor** — When alternating current flows in a circuit, at any instant, the power in watts  $=$  current in amperes  $\times$  potential difference in volts. The practical problem, however, is to find the average value of this product over a complete cycle. When this is done, we get the expression

actual power  $= VI \cos \alpha$ , where

$V$   $=$  voltage recorded by A C voltmeter,

$I$   $=$  current recorded by A C ammeter,

and  $\alpha$   $=$  phase difference between current and voltage

The following three different cases should be noted

(a) A noninductive circuit

Here  $\alpha = 0^\circ$  or the current and the voltage are in step and the power  $= VI$  watts, as in D C

(b) An inductance of very small resistance

In this case  $\alpha$  is very nearly equal to  $90^\circ$ ,  $\cos \alpha = 0$ , and the power  $= 0$ , which means that actually there is no power loss in a reactance such as a

*choke coil*, if the resistance is sufficiently low. This apparently strange result means that the energy stored in the surrounding medium (the magnetic field) in one part of the cycle, returns to the circuit in another. A circuit or part on of a circuit to which this applies is said to be *wattless*. It is for this reason that a choke coil is a more efficient way of changing the strength of an alternating current than an ordinary rheostat in which the power is dissipated as heat.

In a practical choke coil some such device as changing the position of an iron core, enables the operator to alter gradually the magnitude of the inductance and so gradually to vary the current.

(c) An inductive resistance, such as an ordinary electromagnet or the primary of a transformer.

As an illustration, consider an electromagnet, of resistance 50 ohms and inductance 0.3 henry, attached to a supply voltage of 110 A.C. As we have already seen on pages 9 and 14, the impedance is 123.6 ohms, the current 0.89 amperes, and the phase difference between current and voltage  $66^{\circ}8'$ . Hence, the power dissipated in the electromagnet

$$\begin{aligned} &= 110 \times 0.89 \times \cos 66^{\circ}8' \\ &= 110 \times 0.89 \times 0.45 \\ &= 39.6 \text{ watts} \end{aligned}$$

The value of  $\cos \alpha$  (in this example about 0.4) is called the *power factor*. It will be seen that unless its magnitude is known, we cannot find the actual power consumed by an inductive circuit.

The student will realize that instead of using the phase angle, the power factor can be found at once from the ratio  $\frac{\text{resistance}}{\text{impedance}}$ , or, in the above example,

it is equal to  $\frac{50}{123.6}$ .

**13 Capacitance and Phase Difference** — When a circuit attached to an A.C. supply contains capacitance and a negligible resistance, there is again a phase difference between current and voltage, but this time the current is  $90^{\circ}$  ahead of the voltage. If the resistance is not negligible, the phase angle by which the current leads the voltage is less than  $90^{\circ}$ , being in fact equal to the angle  $BAC$  in the triangle of Fig. 9.

As far as phase difference is concerned, it is important to realize that inductance and capacitance have opposite effects: current lagging because of inductance, leading because of capacitance. Hence, in a circuit containing resistance, capacitance and inductance, we may have current either lagging or leading, or, in the special case where the inductive reactance is equal to the

capacitive reactance, the current is in phase with the voltage. The three cases are represented graphically in the diagrams of Figs 12A, 12B, and 12C. In

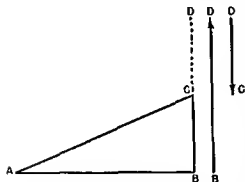


FIG 12A Combination of inductive and capacitive reactance  $BD$  represents the inductive reactance  $DC$  the capacitive reactance,  $AC$  the impedance

value by suitably varying capacitance and inductance. This is of importance when it is desired to reduce power loss. If a given amount of power — so many watts — is to be supplied at a fixed voltage, evidently, since power sup-

each of these figures, the resistance is represented by  $AB$ , the inductive reactance by  $BD$ , the capacitive reactance by  $DC$ , and the impedance by  $AC$ . In Fig 12C, where the inductive reactance is equal to the capacitive reactance,  $ABC$  represents both the resistance and the impedance, and we have the conditions for resonance to which reference was made at the end of section 10

It follows that  $\alpha$ , the phase difference between current and voltage, may be made any desired value by suitably varying capacitance and inductance. This is of importance when it is desired to reduce power loss. If a given amount of power — so many watts — is to be supplied at a fixed voltage, evidently, since power sup-

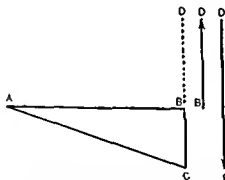


FIG 12B Same as Fig 12A, except that the capacitive reactance is greater than the inductive

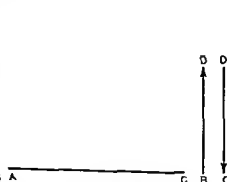


FIG 12C In this case, the capacitive reactance is equal to the inductive

plied  $= VI \cos \alpha$ , the larger the power factor (or the smaller  $\alpha$ ), the smaller the current necessary. Since power loss due to resistance is  $I^2 R$  watts, smaller currents mean smaller power losses

## PROBLEMS AND QUESTIONS

1 Describe a simple experiment to illustrate the difference between an inductive and noninductive circuit

2 Describe, with reference to a simple experiment, the meaning of the inductance of a circuit. What effect has a high inductance when a direct voltage is applied?

3 When 110 volts D.C. are applied to the terminals of an electromagnet, the current is 2.5 amp, whereas when 110 volts A.C. are applied the current is only 0.8 amp. Explain clearly the reason for the difference.

4 An electromagnet has a resistance of 30 ohms and a reactance of 40 ohms (for A.C. of 60 cycles per sec). Find (i) the impedance of the electromagnet, (ii) the inductance in henries. *Ans* (i) 50 ohms, (ii) 0.106 henry

5 Distinguish between impedance and resistance

6 When 60 cycles per sec A.C. is used, the impedance of a coil is found to be 40 ohms. If the resistance of this coil is 10 ohms, find its inductance in henries. *Ans* 0.103

7 The reactance of a coil when used with 60 cycles per sec A.C. is 50 ohms. Find its inductance. *Ans* 0.13 henry

8 When 110 volts alternating are applied to an electromagnet of resistance 30 ohms an A.C. ammeter in the circuit records 0.5 amp. Find (i) the impedance of the electromagnet, (ii) its reactance, and (iii) its inductance (in henries), if the A.C. is 60 cycles per second. *Ans* (i) 220 ohms, (ii) 217.9 ohms, (iii) 0.58

9 When 110 volts alternating, frequency 60 cycles per second, is applied to a coil with some resistance and with inductance equal to  $1/10$  henry, the resulting current is 2.0 amp. Find the current when 110 volts direct is applied to the same coil. *Ans* 2.75

10 (a) When a flat circular coil of 2000 turns, with a mean radius of 5 cm, carries a direct current of 1 amp, the magnetic field inside the coil has a mean value of 50 oersteds. Assuming the field to be uniform, calculate the number of linkages for this current, and hence the inductance of the coil (in henries). (b) If this coil had negligible resistance and 110 volts, 60 cycle per sec alternating, is applied to it, find the current. *Ans* (a)  $7.85 \times 10^6$ , 0.078, (b) 3.7 amp

11 When a coil of resistance 40 ohms is joined to a supply of 110 volts, alternating, an A.C. meter in the circuit records 2.0 amp. Find (i) the inductive reactance of the coil, (ii) its inductance, if the frequency of the A.C. is 60 cycles per second, (iii) the number of linkages when the coil carries a steady current of 2 amp.

12 An incandescent lamp and an electromagnet are joined in series across terminals between which there is a P.D. of (i) 110 volts direct, (ii) 110 volts alternating. In which case is the lamp the brighter? Explain your answer.

13 If the electromagnet in 12 is replaced by a condenser of fairly large capacitance what difference is now observed?

14 One hundred and ten volts, direct, are applied to an electromagnet whose true resistance is 55 ohms. Find (i) the final steady current, (ii) the back E.M.F. (or E.M.F. of inductance) at the instant the current, just after the circuit has been closed, has reached the value 1 amp. *Ans* 55 volts

15 One hundred and ten volts, alternating, are applied to a coil of  $n$  amp turns, whose inductance is 1 henry and resistance 11 ohms joined in series with a condenser of capacitance of 25 microfarads. (a) Calculate for what frequency the inductive reactance is equal to the capacitive reactance. (b) Calculate the current for this frequency. *Ans* (a) 31.8 cycles per sec, (b) 10 amp

## CHAPTER II

### PRODUCTION OF HIGH VOLTAGE PART I. THE INDUCTION COIL AND THE TRANSFORMER

To operate any type of x-ray tube, a voltage very much in excess of those encountered in ordinary circuits must be available. Actual values range from less than 10,000 to more than 1,000,000 volts. In this chapter, our attention is confined to means of obtaining potential differences which do not exceed 200 000 or 250 000 volts.

**14 The Induction Coil** — In the early days of x-rays the induction coil was the apparatus used for developing the voltage necessary to operate an x-ray tube. Although the coil is practically obsolete in modern roentgenology, it still has its uses, in the physiology laboratory, for example, and the student is well advised to recall its main features. The basic principle is that of electromagnetic induction. A direct current flowing in a primary coil wrapped about an iron core is regularly made and interrupted, and, in consequence, an induced E M F is developed in a secondary coil wrapped about the primary. On

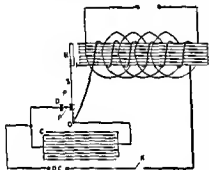


FIG. 13 Primary and secondary circuits of an induction coil with hammer break

“make” of the primary circuit, when the lines of force are introduced, this E M F is in one direction, on “break,” when the lines disappear, in the opposite direction.

To make and break the primary circuit, an *interrupter* is used. At one time three different types, the hammer, the mercury, and the electrolytic were in general use, the last two being suitable when heavy power loads were needed. As the transformer has entirely superseded the coil where heavy loads are concerned in this text reference is made only to the hammer interrupter. Figure 13 shows the essential features. When the switch *K* is closed, a direct current flows in the primary coil provided the contact points *P* and *P*<sub>1</sub> are touching. One of these contacts *P* is at the end of a screw passing through the rigid support *D*. The other *P*<sub>1</sub> is attached to the metal spring *S* which in its turn is rigidly fastened at the end *O* but is free to vibrate at the other end. At this

end it is loaded with the piece of soft iron  $H$ . Normally, when no current is flowing,  $P$  and  $P_1$  are in contact. Hence, on closing the switch  $K$ , the circuit is completed, a current flows, the iron core is magnetized, the hammer  $H$  is attracted, the spring moves to the dotted position, the contact points  $P$  and  $P_1$  are separated, and the circuit broken. The primary current then drops to zero, the core loses its magnetism and the hammer is pulled back to its initial position by the elasticity of the spring  $S$ , aided by an additional spring not shown in the diagram. The action, which so far is essentially the same as that of an electric bell, is then repeated, the primary circuit being automatically made and broken, with a resulting induced E M F in the secondary, in one direction on make, in the opposite on break.

By using a large number of turns in the secondary very high E M F may be induced, provided the magnetic lines are introduced or removed quickly

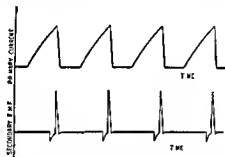


FIG. 14. Graphical representation of primary current and of secondary voltage in simple induction coil

enough, that is, provided the time of make or of break is short enough. Actually, in a good induction coil, the time of break is so much less than that of make that the E M F induced in the secondary on break is enormously greater than that on make. In a small coil used by the students in one of the writer's classes, on a single break of the primary, it is possible to obtain a spark between the secondary terminals of about one centimeter, whereas on make the E M F is so small that no spark at all can be detected. The explanation for this difference depends on more than one factor. To begin with, because of the E M F of inductance in the primary coil itself (see section 6), there is a delay in the rise of the current to its maximum value and the time of make is prolonged. For the same reason, on break, unless special precautions are taken, the E M F of inductance causes marked sparking at the contact points (where the break occurs), sparking which may be followed by vaporization of the metallic terminals and resultant arcing. To suppress this sparking and arcing, which prolongs the time of break, a condenser  $C$  is placed across the contact points. This

condenser prolongs still further the time of make, because on make a certain quantity of electricity flows into it. On break, the induced E M F causes a further charging of the condenser and the current is not prolonged by bad sparking and arcing. If the mechanical device pulls the points apart quickly, then a very rapid break is made, with a corresponding high E M F in the secondary. In a good coil this E M F, as already noted, is so much greater than that induced on make, that the secondary terminals may be marked, one positive, the other negative, as if the coil developed a unidirectional high voltage. In a poor coil, this is far from being so.

In Fig 14, the graphs give a general idea of the behavior of the primary current and the corresponding E M F induced in the secondary.

The name *faradic* is sometimes given to induction coil currents. It will be seen that they are characterized by abrupt changes, markedly different from the smooth, gradual changes of sinusoidal currents (see section 81).

**15 The Transformer** — For voltages up to about a quarter of a million, the common device used in x-ray outfits is the transformer. Here again the principle is that of electromagnetic induction. In Fig 15, *ABCD* represents a series of sheets of soft iron put together to form a core of the shape illustrated. A coil of wire *P* the primary, connected to an alternating source of potential difference, is wrapped about one arm of the iron core, while a second coil *S*,

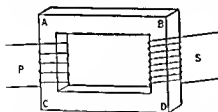


FIG 15 Primary and secondary of a simple closed core transformer

the secondary, is wrapped about another part (or overlapping the primary). When the primary circuit is closed, the resulting magnetic field is continuously changing, the number of lines rising to a maximum in one direction, then decreasing to zero, then increasing in the opposite direction. Whenever the number of linkages is increasing,\* there is an induced

E M F in the secondary in one direction, but when the number is decreasing (or increasing with the lines reversed) the E M F is in the opposite direction. The induced voltage in the secondary, therefore is alternating and of the same frequency as that of the primary current the relation between the two being somewhat as shown in Fig 16.

The magnitude of the secondary E M F is approximately as many times greater (or less) than the primary voltage as the total number of turns in the

\* An increase of lines in one direction has the same effect as a decrease of lines in the opposite direction.

secondary is greater (or less) than the number in the primary. To understand why this is so, it is necessary to realize that there is an induced E M F (the E M F of inductance discussed in section 6) in the primary coil itself and that, when the secondary circuit is open so that no power is taken from the transformer, the only function of the primary current is to maintain the alternating magnetic field. Only a small current is necessary for this. If the primary resistance is small, the actual voltage necessary to maintain the current is very small also and therefore the E M F of inductance is almost equal to the

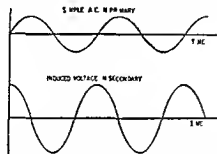


FIG. 16. Graphical representation of current in primary of a transformer and of corresponding induced voltage in secondary

applied voltage, just as when a direct current motor is running freely without any external load, the back E M F in the armature is almost equal to the applied voltage. Now since the same lines of force cut each turn of both primary and secondary, the induced E M F per turn in the secondary must be equal to the induced E M F per turn in the primary. Hence,

$$\text{resultant secondary E M F} = \text{E M F of inductance in primary} \\ \times \frac{\text{number of turns in secondary}}{\text{number of turns in primary}}.$$

Therefore, since applied voltage across primary is nearly = E M F of inductance, we may write with little error,

$$\text{E M F in secondary} = \text{primary voltage} \times \frac{\text{number of turns in secondary}}{\text{number of turns in primary}}.$$

Thus, if 110 volts are applied to the primary of a transformer for which the ratio of secondary to primary turns is 1000, the secondary E M F. is about 110,000 volts.

The secondary E M F may be either higher or lower than the primary voltage. In a *step down* transformer, such as is used for heating the filament of an x-ray tube (section 58) or a rectifying valve (section 57), the voltage is



lowered. In *step-up* transformers, the secondary voltage is greater, and as we have already seen, may reach or exceed 250,000 volts.

**16. Insulation.**—As the high tension voltage becomes greater, the problem of good insulation becomes more difficult. Injurious sparking may occur between different parts of the secondary or between the secondary and its surroundings. At one time some x-ray transformers were impregnated with wax, but this method proved unsatisfactory even for only moderately high voltages. Air bubbles developed and sparking took place through the cavities thus formed. Good high tension transformers are now immersed in oil, a method which not only provides better insulation but has the further advantage that because of convection currents heat is dispersed more rapidly.

**17. Efficiency and Power Rating of Transformers** — When the secondary circuit is closed, a current flows and power is delivered to this circuit. Automatically\* more power is delivered by the supply source to the primary. The transformer, therefore, may be looked on as a mechanism for receiving power at one voltage and current and delivering it at a different voltage and current. Inevitably there is some loss in the transaction, although a good transformer may have an efficiency greater than 95 per cent. The energy losses may be grouped under two headings: (a) iron losses, (b) copper losses. Under (a) we include (i) the loss due to hysteresis, arising from the magnetizing and demagnetizing of the iron core, and (ii) the loss due to eddy currents in the mass of the metal. The former loss is reduced by choosing a type of iron in which the magnetism lags behind the magnetizing field as little as possible, and the latter loss by the use of laminated cores.

Copper loss is the name given to the heat loss arising from the resistance of the wire carrying the current. The magnitude of this is equal to  $I^2R$  watts, where  $I$  is the customary symbol for the current in amperes, and  $R$  the resistance in ohms.

Even when all these losses are kept to a minimum, high efficiency is not obtained unless the primary and secondary coils are more closely coupled than they are in Fig. 15. Good coupling is obtained by winding the primary and the secondary close together, but the aim of this text is to explain principles

\* The complete explanation of the reason for this is not simple, but a general idea may be had from the following. By Lenz's law any induced current opposes the movement of the magnetic lines which cause it. Therefore, the secondary current will oppose the changing magnetic flux. If lines are on the increase, it will create a counterfield opposing the increase. This reduction in flux will lessen the opposing F M F of induction in the primary, and hence the primary current will automatically increase.

rather than technical details, exact methods of constructing transformers will not be described.

In ordinary problems it is usual to assume that the transformer is 100% efficient. The following example may be useful.

*In a step up transformer, the secondary has 1000 times as many turns as the primary. If 10 milliamperes are delivered at 100,000 volts, find (i) the primary current, (ii) the primary voltage.*

Since the secondary E.M.F. is 100,000 volts, and the ratio of the number of turns in secondary to that in primary is 1000,

$$\text{primary voltage} = \frac{100,000}{1000} = 100 \text{ volts}$$

If the transformer is 100% efficient, then primary voltage  $\times$  primary current = secondary voltage  $\times$  secondary current, or

$$100 \times I_p = 100,000 \times 0.010$$

or

$$I_p = 10 \text{ amperes}$$

Or, alternately we may find the primary current at once, from the fact that, if the secondary voltage is 1000 times greater than that applied to the primary, the secondary current must be 1000 times less. Hence,

$$\begin{aligned} \text{primary current} &= 0.010 \times 1000 \\ &= 10 \text{ amperes} \end{aligned}$$

**18. Transformer Rating.**—When a radiologist buys an x-ray transformer, he is interested in knowing not only what maximum voltage a machine is able to develop but also what current it will deliver at this or lower voltages. Bearing this in mind, at least one firm\* has adopted a standard means of specifying, under three conditions of usage, the peak voltage† (not the R.M.S. value), and the corresponding current as read on the milliammeter placed in the secondary circuit (see section 20). The three conditions are (a) continuous use of the transformer, (b) use for a "short" period, that is, for a time not exceeding 30 seconds, with rest intervals five times as long, and (c) momentary use, that is, for a time not exceeding 1 second, with a rest period of at least a minute in between. For example, a certain transformer is advertised as having an output of 120,000 volts, peak, at 25 ma. for continuous use, or 110,000 volts at 60 ma. for a short time, or 100,000 volts at 100 ma., for momentary use.

\* Watson & Sons (Electro Medical) Ltd., London, England.

† In many branches of x-ray work, as will be seen later, the peak voltage is more important than the average value.

## PRODUCTION OF HIGH VOLTAGE

19 Rectification. — For the satisfactory use of an x-ray tube the voltage applied to it must be unidirectional. It may be intermittent, but unless its direction is always the same (and correct) the effect on the tube may be disastrous. As a rule, therefore, since the high tension transformer develops an alternating E M F some rectifying device is needed so that the voltage applied to the tube is always in the same direction. Rectification of this kind

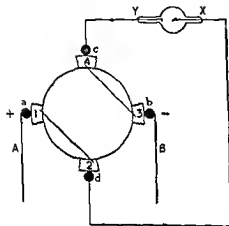


FIG 17 Rectifying disc. Wires A and B are joined to secondary of transformer

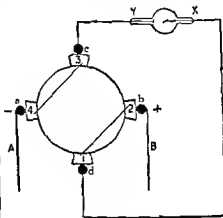


FIG 18 Position of rectifying disc one half cycle after that of Fig 17

is done either by a *mechanical rectifier* or a *rectifying valve*, using a heated filament. Although the latter method has almost superseded the former, an explanation of its use must be postponed until the important principle of thermionic emission has been discussed (in section 56).

The principle of the mechanical rectifier should be clear from a consideration of Figs 17 and 18. In these figures A and B represent heavy lead wire coming directly from the high voltage side of a transformer. Each circle represents a disc which may be rapidly rotated and is made of some good insulating material. Attached to the disc are four projecting pieces of metal (1, 2, 3, 4), 1 and 2 being connected by a piece of wire or strip of metal, similarly 3 and 4. As the disc revolves, these pieces touch fixed metal brushes (a, b, c, d), a and b being attached to the lead wire A and B, while by means of c and d, connection may be made with a circuit containing an x-ray tube. Suppose, now, that as the disc rotates, it reaches the position indicated in Fig 17 at the moment the voltage between A and B is a maximum (the "peak" of the sinusoidal curve), A being +, B -. At that instant, then,

a current will flow from *A* to *a* to 1 to 2 to *d*, through the bulb in direction *X* to *Y*, back to *c* to 4 to 3 to *b* to the other lead wire *B*. Suppose further that during the time of one half a cycle, the disc revolves to the position shown in Fig 18. In that case, since the voltage between *A* and *B* is now once more a maximum but with *A*— and *B*+, a simple inspection of the diagram in Fig 18 will show that the current flows from *B* to *b* to 2 to 1, through the bulb in the same direction as before, to 3 to 4 to *a* to *A*. In other words, if the disc can be rotated at this very exact speed, then the current through the bulb will always be unidirectional. In the secondary coil of the transformer, of course, it is alternating, just as before. This exact co relation between the speed of the rectifying disc and the frequency of the alternating current is obtained by means of what is called a *synchronous motor*. This is an A C motor which runs at a single speed only, because its armature changes

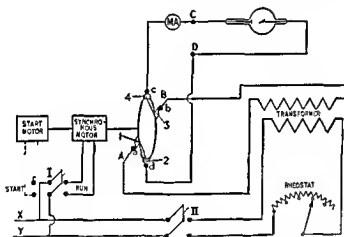


FIG 19 Simplified connections of a transformer high tension circuit, with mechanical rectifier

its position in exact synchronism with the changes of the current. An x-ray transformer outfit with mechanical rectifier must include such a motor, solely for the purpose of keeping the rectifying disc revolving at the critical speed. Moreover, since the synchronous motor runs at one speed only, frequently a second (starting) motor is necessary in order to bring the synchronous motor up to the desired speed. Sometimes the use of a second motor is avoided by having a synchronous motor constructed with an additional circuit which, by means of a special starting switch, is put in use for a few seconds and enables the machine to run as a different kind of motor until the critical speed is reached.

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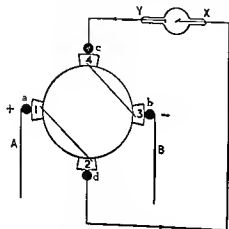


FIG 17 Rectifying disc Wires A and B are joined to secondary of transformer

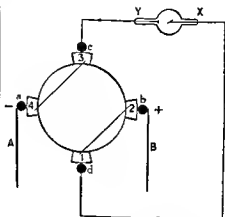


FIG 18 Position of rectifying disc one half cycle after that of Fig 17

is done either by a *mechanical rectifier* or a *rectifying valve*, using a heated filament. Although the latter method has almost superseded the former, an explanation of its use must be postponed until the important principle of thermionic emission has been discussed (in section 56).

The principle of the mechanical rectifier should be clear from a consideration of Figs 17 and 18. In these figures A and B represent heavy lead wire coming directly from the high voltage side of a transformer. Each circle represents a disc which may be rapidly rotated and is made of some good insulating material. Attached to the disc are four projecting pieces of metal (1, 2, 3, 4), 1 and 2 being connected by a piece of wire or strip of metal, similarly 3 and 4. As the disc revolves, these pieces touch fixed metal brushes (a, b, c, d), a and b being attached to the lead wire A and B, while by means of c and d, connection may be made with a circuit containing an x-ray tube. Suppose, now, that as the disc rotates, it reaches the position indicated in Fig 17 at the moment the voltage between A and B is a maximum (the "peak" of the sinusoidal curve), A being +, B -. At that instant, then,

a current will flow from *A* to *a* to 1 to 2 to *d*, through the bulb in direction *X* to *Y*, back to *c* to 4 to 3 to *b* to the other lead wire *B*. Suppose further that during the time of one half a cycle, the disc revolves to the position shown in Fig 18. In that case, since the voltage between *A* and *B* is now once more a maximum but with *A*— and *B*+, a simple inspection of the diagram in Fig 18 will show that the current flows from *B* to *b* to 2 to 1, through the bulb in the same direction as before, to 3 to 4 to *a* to *A*. In other words, *if the disc can be rotated at this very exact speed*, then the current through the bulb will always be unidirectional. In the secondary coil of the transformer, of course, it is alternating, just as before. This exact co-relation between the speed of the rectifying disc and the frequency of the alternating current is obtained by means of what is called a *synchronous motor*. This is an A.C. motor which runs at a single speed only, because its armature changes

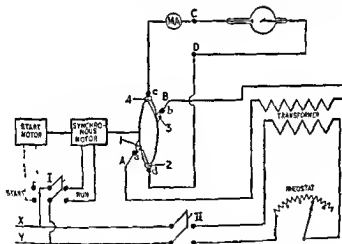


FIG 19 Simplified connections of a transformer high tension circuit, with mechanical rectifier

its position in exact synchronism with the changes of the current. An x-ray transformer outfit with mechanical rectifier must include such a motor, solely for the purpose of keeping the rectifying disc revolving at the critical speed. Moreover, since the synchronous motor runs at one speed only, frequently a second (starting) motor is necessary in order to bring the synchronous motor up to the desired speed. Sometimes the use of a second motor is avoided by having a synchronous motor constructed with an additional circuit which, by means of a special starting switch, is put in use for a few seconds and enables the machine to run as a different kind of motor until the critical speed is reached.

**20 Operation of Transformer with Mechanical Rectifier.** — A complete circuit, somewhat simplified, is shown in Fig 19, where *X* and *Y* represent supply terminals, 110 or 220 A C. The supply mains branch into two circuits, one supplying current to the synchronous motor, and controlled by switch I, the other supplying current to the primary of the high tension transformer, controlled by switch II. In addition, there is the high tension circuit, including the secondary of the transformer, the x-ray tube and a milliammeter *MA*, with the rectifying disc placed so as to send a unidirectional current through the tube. The diagram should make clear without further explanation the connections of the tube circuit. It may be stated, however, that the parts of the rectifying arrangement are labeled as in Figs 17 and 18.

To operate with such an arrangement, the tube\* is first placed in position and connected to the high tension terminals *C* and *D*. This circuit is then closed as illustrated in the figure. Next the synchronous motor is brought up to speed. In the arrangement we are considering this is done by throwing switch I to the side marked "start," thus utilizing the starting motor, until the requisite speed is attained. Switch I is then thrown to side marked "run" and left there. The rectifying disc is now running at the necessary exact speed and may be left so for some length of time. In another machine, as already noted, there might be only a single motor, with special starting switch closed initially for two or three seconds.

Finally, switch II, the so called x ray switch, is closed, thus allowing current to flow in the primary of the transformer. The resulting high induced E M F in the secondary then causes a current through the tube and milliammeter. The purpose of the rheostat is to alter the primary voltage, and hence the voltage applied to the tube, but that is a question we shall discuss in detail in the next chapter.

**21 Nature of Tube Current** — With such an arrangement it should not be difficult to see that the tube current is intermittent. A glance at Fig 20 should make it clear that when the disc is in the position indicated in that diagram, there is no current through the tube because neither *a* nor *b* touches a metal projection. Evidently the length of time the current is flowing will depend on the size and shape of the projecting pieces, that is, on the time they are in electrical contact with the lead wires *A* and *B*. This time interval, therefore, may be and probably is different in different machines. If it is very short, only the "peaks" of the voltage values will be utilized as

\* In a modern x ray tube, an additional circuit for heating the tube filament is necessary (Chapter VI). This, however, does not alter the principle of the general arrangement explained at this stage.

represented graphically by the short heavy line in Fig 21a. If the time interval is a little longer, a greater portion of the whole range of voltage values will be utilized, the short heavy lines extending to the dotted parts. It is well to note further that, in order to utilize the peak voltage, the disc must be in proper alignment, that is, when it is in the position represented by Fig 17, the voltage across *A* and *B* must be at its maximum value. Sometimes the disc slips on its rotating axis and gets out of alignment. To readjust it the services of an electrical engineer may be necessary.

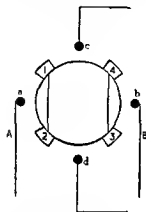


FIG 20 Position of rectifying disc when no current is passing

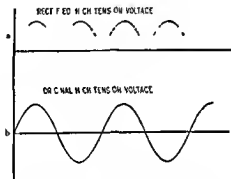


FIG 21 Graphs to show intermittent nature of voltage applied to a tube when a rectifying disc is used

**22 Polarity Indicator** — Not only must the current through an x-ray tube be unidirectional but it must be in the right direction. Now, if one went through the series of operations which have just been outlined, it might be found on closing switch II that the voltage was applied to the tube in the wrong way. Just how one would know that will be explained later. In fact, if one began one hundred times at the beginning, with all switches open, it would be found on closing the x ray switch II, that on the average fifty times the voltage was right, fifty times wrong. In other words, with the above procedure, it is just an even chance whether the voltage is right or wrong. A glance at Fig 17 will explain the reason for this. In this figure it has been assumed that when the disc is in the position indicated, *A* is positive and *B* negative. Now, when it is brought up to speed, there is just as good a chance of *A* being negative and *B* positive, as vice versa. With the above simplified arrangement, therefore, when the x ray switch is closed, one would never know whether the voltage applied to the tube would be in the right or the



wrong direction. If it were wrong, it would then be necessary to open the motor switch and close it again until the right direction was obtained. This can be avoided by the use of a *polarity indicator*, a small instrument found on the control board of mechanical rectifier x-ray outfits. It is essentially a direct current meter, with a pointer which moves to the left for current in one direction, to the right for current in the opposite direction. The indicator is placed in a branch circuit taken off the motor circuit, and when the motor switch is closed, a current rectified by a commutator device on the motor shaft flows through it. Depending on which way the current has been rectified, the pointer moves to one side or to the other. By a single observation the operator can find out which side corresponds to correct polarity for the tube, and ever afterwards by looking at his indicator, he knows, *without closing the x ray switch*, whether the rectified voltage is correct or not. If on starting the motor the pointer on the polarity indicator is in the wrong direction, by throwing over a reversing switch in the primary circuit, the operator makes sure without stopping and restarting the motor, that the secondary voltage will be in the right direction.

As already noted, mechanical rectifiers are now largely replaced by hot filament valves, which, as we shall see later, require no motors and revolving discs, with their attendant noise. A full discussion of valve rectifiers and associated high tension circuits, with and without condensers, is given in Chapter VII.

### PROBLEMS AND QUESTIONS

- 1 What information should be given about the output of a transformer for x ray work?
- 2 In a step up transformer, the secondary has 1000 times as many turns as the primary. When 10 ma are delivered at 100 000 volts what is the current in the primary circuit? (Assume the transformer 100 per cent efficient.)
- 3 What is the special feature about a synchronous motor?
- 4 What is a rectifying disc and how is it used? Illustrate your answer by a diagram or diagrams.
- 5 By means of a diagram, show how the current in the primary of a good induction coil varies with the time. Hence explain the relative magnitude of the E M F induced in the secondary on make as compared with break.
- 6 Make a careful circuit diagram of an induction coil with hammer break and condenser.
- 7 By means of two diagrams explain the principle of rectification by a rectifying disc. Why is the disc of fairly large dimensions when used in an x ray circuit?
- 8 Draw a graph indicating the nature of the tube current when voltage rectified by a rectifying disc is applied to an x ray tube.

## CHAPTER III

### MEASUREMENTS AND CONTROL OF HIGH TENSION VOLTAGE

In operating roentgen tubes it is highly important not only to be able to vary the voltage applied to the tube, but also to know its actual magnitude. In this chapter important methods of doing these things are discussed. Reference is first made to several methods of measuring high voltages.

**23. Spark-gap Meter.**—The principle of this method is extremely simple—the greater the potential difference between two conductors, the longer the spark between them when the air insulation breaks down. Spark lengths may thus be equated to corresponding voltages, but in doing so one or two precautions must be considered. To begin with, the spark length depends on the shape and size of the conductors, as well as the potential difference between them. The same voltage gives a different length between two pointed than between two spherical conductors, and still different if one conductor is a sharp point, the other a plane. The length even varies for spherical conductors of different diameters, as will be seen by a glance at Table II (taken from Kaye and Laby's Tables).\*

It will be noted that the lengths given in this table are for air at 25°C and 760 mm pressure. For different values of both temperature and pressure, a correction must be made because these factors also affect the spark length for a given voltage. Table III, for example, gives the correction which must be applied to the values given in Table II, for a few other temperatures and pressures. To illustrate, with spheres of diameter 10 cm, at a pressure = 740 mm, and temperature = 20°C, the voltage corresponding to a spark length of 2.02 cm, is not 60,000 but  $60,000 \times 0.99$ .

To some extent the spark-over voltage depends also on the humidity of the air, and for highly accurate work correction has to be made for this factor. A. B. Lewis has shown that, for voltages of the order of 10,000, there is an increase in spark-over voltage, for a fixed gap, amounting to 0.13 per cent for each millimeter of vapor pressure of water in the atmosphere.

\* "Physical and Chemical Constants and Some Mathematical Functions," by G. W. C. Kaye and T. H. Laby. Longmans, Green and Co.

TABLE II — (SPARKING VOLTAGES AT 25° C AND 760 MM PRESSURE)

Kilo Volts (Peak)	Needle Points No 00 New Sewing Needles		Spheres		
			Diameter 5 cms	Diameter 10 cms	Diameter 25 cms
	cms gap	inches gap	cms gap	cms gap	cms gap
10			0 29	0 30	0 32
15	1 30	0 51	0 44	0 46	0 48
20	1 75	0 69	0 60	0 62	0 64
25	2 20	0 87	0 77	0 78	0 81
30	2 69	1 06	0 94	0 95	0 98
35	3 20	1 26	1 12	1 12	1 15
40	3 81	1 50	1 30	1 29	1 32
45	4 49	1 77	1 50	1 47	1 49
50	5 20	2 05	1 71	1 65	1 66
60	6 81	2 68	2 17	2 02	2 01
70	8 81	3 47	2 68	2 42	2 37
80			3 26	2 84	2 74
90			3 94	3 28	3 11
100			4 77	3 75	3 49
110			5 79	4 25	3 88
120				4 78	4 28
130				5 35	4 69
140				5 97	5 10
150				6 64	5 52
160				7 37	5 95
170				8 16	6 39
180				9 03	6 84
190				10 0	7 30
200				11 0	7 76
210					8 24
220					8 73
230					9 24
240					9 76
250					10 3

TABLE III

Temp	Pressure, 720 mm	Pressure, 740 mm	Pressure, 760 mm	Pressure, 780 mm
0°	1 04	1 06	1 09	1 12
10	1 00	1 03	1 05	1 08
20	0 96	0 99	1 02	1 04
30	0 93	0 96	0 98	1 01

In actual use a spark gap meter with spheres of a standard size is placed across the terminals of the tube, as shown in Fig 22. With the tube running, the distance between the gap terminals is gradually lessened until a spark takes place. To protect the surfaces of the spheres from injury due to excessive sparking, series resistances  $RR$  of many thousand ohms should be placed as illustrated. It is important to note that a current should actually be flowing through the tube when the reading is taken. If no current is in the tube circuit, the length of the spark measures the E M F or maximum voltage got up by the transformer. When a current is flowing, the voltage across the tube is less, sometimes very much less, than this E M F because of the drop in potential in the secondary coil. (See also section 25.)

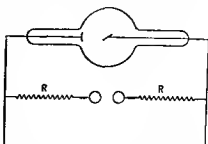


FIG 22 Sphere gap with protecting resistors for measurement of voltage across an x ray tube

**24. Corona** — Before leaving the subject of sparking potentials, attention is directed to the difference between a spark and *corona* or *brush* discharge. In the case of a spark the electric field between two conductors (one of which may be the earth) becomes so intense that the air resistance breaks down along what is practically a continuous path between them. A discharge passes, accompanied by a crackling sound and marked luminosity. If a conductor is at high potential, the air in its immediate vicinity may become conducting without a complete breakdown between it and another conductor. In this case, a feeble discharge takes place, accompanied by a glow called the *corona*, which can be seen in a darkened room. The smaller the dimensions of the conductor, the more the likelihood of a corona discharge. In the early days of roentgenology, the high tension leads running to the x ray tube were frequently narrow wires which were wound on a small reel. With these marked corona was a common experience. Corona is undesirable, because it means not only a loss of energy, but also the danger of the formation of undesirable ozone and oxides of nitrogen. It can be avoided, as it now invariably is, by the use of conductors of large size, kept well apart and well away from the earth.

**25. Primary Voltmeter** — The most common and certainly the most convenient, if not the most accurate, method of measuring the potential difference across the terminals of a tube consists in the use of an ordinary A C voltmeter across the primary terminals of the transformer. The higher the

primary voltage, the greater the E M F in the secondary and the greater the voltage across the tube. Hence in any given outfit, the scale of the voltmeter may be marked to read tube voltage instead of the primary voltage which it really records. Unfortunately the scale can be exact for only one value of the tube current. It is true that for each primary voltage, there is a corresponding E M F induced in the secondary, but, as we have already noted, when a current is flowing in the tube circuit, the potential difference across the tube terminals is less than the E M F because of the voltage drop in the secondary winding. Now this voltage drop depends on the current, being greater the greater the current, hence for the same primary reading of the voltmeter the potential difference across the tube will decrease as the tube current increases. For example, in a certain x-ray transformer, for a primary voltage of 80, a spark-gap meter across a tube gave a reading of 3.06 inches for a tube current of 10 ma, but only 2.85 inches for a current of 30 ma, or, for a primary reading of 100 volts, the spark length was 4.51 inches for 10 ma, but only 4.10 inches for 30 ma.

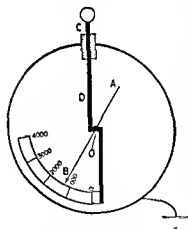


FIG 23 The Braun electrostatic voltmeter

For very exact work, therefore, it would be necessary to have a separate scale on the primary voltmeter for each tube current. If the tube is to be used with only a narrow range of currents, this is not necessary, and, in any case, a primary voltmeter calibrated to read tube kilovolts for a single milli-ampereage is an extremely useful feature of an x-ray transformer outfit. Frequently all that an operator wishes is to operate his tube at the same voltage as used previously, with the same tube current.

**26 Electrostatic Voltmeter.**—An ordinary "gold-leaf" electroscope is an electrostatic voltmeter, the deflection of the leaf measuring the potential difference be-

tween the charged system and the surrounding earthed case. In the Braun electrostatic voltmeter, this is put to practical use for measuring voltages of the order of a few thousand. In this instrument, a movable metal strip *AB*, Fig 23, pivoted at *O*, is in electrical contact with the insulated metal rod *CD*. The surrounding case is grounded. When *CD* is joined to a conductor charged to high potential (for example, to one knob of a Wimshurst electrostatic machine, whose other knob is grounded), the movable rod is deflected an amount which is greater, the higher the potential.

For higher potentials use is made of the fundamental principle, that, if a potential difference of  $V$  volts exists between two charged conductors, one positive, the other negative, they are attracted with a force whose magnitude depends on the distance between the conductors, and on the voltage, being directly proportional to  $V^2$ . If, then, two plates such as  $A$  and  $B$ , Fig. 24, are maintained at the potential difference to be measured, the force of attraction between them is proportional to the magnitude of this potential difference. If one plate is fixed and the other free to move, this force may be measured,\* or the arrangement may be such that a pointer moves over a scale an amount which is greater, the greater the force, that is, the greater the potential difference to be measured.

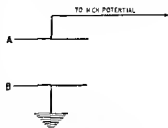


FIG. 24 If conductor  $A$  is maintained at a potential  $V$  and conductor  $B$  is joined to ground,  $A$  and  $B$  are attracted with a force which is proportional to  $V^2$ .

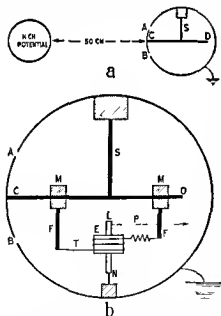


FIG. 25 An electrostatic voltmeter in which potentials of the order of 250,000 volts are measured by the movement of the sector  $AB$ .

As an illustration of an electrostatic voltmeter used for voltages of the order of a quarter of a million, a brief description is given of one constructed in the Palmer Physics Laboratory at Princeton University, and described in an article by C. W. Lampson. In this instrument the electrostatic pull is measured by the application of a simple principle in mechanics. If the bob of a simple pendulum is pulled aside by a horizontal force  $F$ , the greater  $F$  the greater the horizontal displacement  $x$ . If the ball is very heavy, so that it is never deflected a great deal out of the vertical, the displacement  $x$  is directly proportional to the force  $F$ .

In this type of electrostatic voltmeter, a sector  $AB$ , Fig. 25, is punched out of an 8" hollow copper sphere and then suspended so that it is

\* In one standard arrangement it is weighed because the movable plate is attached to one arm of a balance.

free to move horizontally with only a small amount of clearance between the sector and the remainder of the sphere. A rod  $CD$  is rigidly attached to the sector  $AB$  and the whole hung by a suspension  $S^*$ . A silk thread  $T$  is stretched between the ends of brass rods  $F$  and  $F'$ , attached to collars  $M$  and  $M'$  which are rigidly joined to the rod  $CD$ . This thread, kept under tension by a small metal spring, is wrapped around a drum  $E$  attached to the vertical cylinder  $LN$ , which is pivoted between fixed supports so that it is free to rotate.

Now when the voltmeter, which is grounded, is brought in the neighborhood of a terminal charged to a potential  $V$ , as in Fig. 25a, the plate  $AB$  is pulled with a force, whose magnitude, as we have already noted, is proportional to  $V^2$ . The plate, therefore, and the whole system to which it is attached moves in a horizontal direction an amount proportional to this force. Because of the action of the thread wrapped about the drum, the cylinder is rotated a corresponding amount, and finally, the end of a pointer  $P$  attached to the cylinder, moves over a scale. Thus, "the lateral motion of the sector is transmitted as rotatory motion to the pointer." The position of the pointer on the scale, therefore, indicates the magnitude of the pull on the plate, that is, of the potential difference between the source of high potential and the grounded voltmeter. To read in volts the scale must be calibrated. In the instrument used at Princeton calibration was carried out by the use of a high resistance and measured current as explained in the next section, and also by absolute calculation from fundamental principles of electrostatics and mechanics.

**27 Current through a High Resistance** — The student will recall that when a direct current of  $I$  amperes flows in a resistance of  $R$  ohms, the potential difference between the ends of the wire is  $IR$  volts. For example, if a milliammeter indicates a current of 10 ma. in a megohm, or 1,000,000 ohm, resistance, the potential difference across it is  $1,000,000 \times 0.010$ , or 10,000 volts. Given a sufficiently high resistance, therefore, it is possible to measure voltages of the order of those used in x ray work, provided a suitable instrument is available for observing the (small) current through the resistance when the high voltage is applied across it.

F. D. Owen-King has described in the British Journal of Radiology another method of utilizing a high resistance to measure the voltage across an x ray tube when operated with constant potential outfits. This method, which it is stated, measures 250,000 volts with an accuracy of 2 per cent, consists in measuring the voltage across a very small portion  $CB$ , Fig. 26, of the high

\* The sphere is cut into two hemispheres to enable the apparatus to be placed within it, the two parts being subsequently put together again.

resistance  $AB$  through which a small current flows as a result of the application of the tube voltage. The potential difference between  $A$  and  $B$  is then many times greater than that recorded by the voltmeter attached to  $B$  and  $C$  as the resistance of  $AB$  is greater than that of  $CB$ . For the satisfactory operation of this arrangement, certain special constant "Carbo" resistances were utilized. These are "of specially prepared resistance material immersed in oil and contained in porcelain tubes, the oil serving the purpose of cooling the resistance units and preventing corona effects."

Further details concerning this method will be found in section 186, and in Fig. 182, p. 255, the reader will find an actual photograph of a high resistance used for the measurement of high voltages.

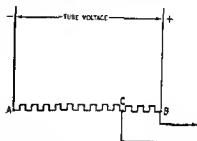


FIG. 26 By measurement of the voltage across  $BC$  a small portion of the very high resistance  $AB$  in parallel with an x-ray tube the potential difference across the tube may be measured.

## 28 The Seeman Spectrograph

— This instrument provides an accurate means of measuring the maximum potential difference across a tube from observation of the spectrum of the x-rays emitted by the tube. An explanation of the principle involved must be postponed until we are dealing with the nature of x-rays (see section 117).

**29. Control of Tube Voltage by Rheostat** — With the standard transformer arrangement, the voltage across an x-ray tube may be altered and controlled by two standard means (1) the rheostat, and (2) the auto-transformer.

In the rheostat use is made of the familiar  $IR$  drop in voltage due to resistance (see section 27 again). Suppose the circuit which includes the primary of the transformer is arranged as in Fig. 27. If, at the main supply terminals, the voltage is 220 A.C., then with this arrangement, the voltage across  $GD$ , the primary of the high tens on transformer, is less than 220 by an amount which depends on the resistance of the rheostat and the current. By decreasing the amount of resistance (if the power taken from the transformer remains constant), the voltage drop in the rheostat becomes less and, therefore, the voltage across the primary greater.

In considering the rheostat method of control of voltage, one or two points should be noted.



(a) A great deal of heat is developed in a rheostat, because whenever a current flows against resistance, there is a loss in power equal to  $I^2R$  watts

(b) Since the drop in voltage through the rheostat depends on the values of both resistance and current, a change in the current may mean a marked change in tube voltage, even for the same setting of the rheostat. For example, if the tube current is cut off without opening the primary circuit\* of the transformer, the supply current in the primary circuit drops to a low value, the  $IR$  drop in the rheostat becomes much smaller, the voltage across the primary much larger, and, therefore, the E M F in the secondary much greater. This is a disadvantage, because an unduly high voltage may then be applied to the tube.

On the other hand, if because of a short circuit in the tube circuit, the current supplied the primary should suddenly rise, the rheostat control has the advantage that automatically the tube voltage will drop. In this case, the

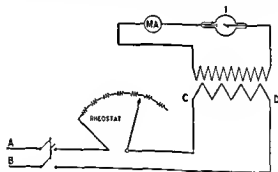


FIG. 27 Connections for simple rheostat control of high tension voltage

sudden rise in current greatly increases the  $IR$  drop in the rheostat and so causes a corresponding decrease in voltage across the primary. The rheostat can then be considered as a kind of safety valve in the case of a short circuit.

**30 Voltage Control by Auto-transformer.**—With the type of x-ray tube now in common use, the usual method for controlling tube voltage is by means of an *auto-transformer*. This is essentially a transformer with a single winding whose ends are connected, as shown in Fig. 28, to the low voltage A.C. supply mains. From B, one end of the winding and C a point whose position may be varied by the use of a number of tappings, wires are led to the primary of the high tension transformer. Because of the principle

\* As will be seen in Chapter VI, this can be done in hot filament tubes simply by opening the filament circuit.

of electromagnetic induction, between *B* and *C* a voltage is maintained whose magnitude is in the same ratio to the supply voltage as the number of turns of the winding between *B* and *C* is to the number between *A* and *B*. By altering the position of *C*, voltages ranging from zero to the full supply voltage may be applied to the primary of the high tension transformer, and so a corresponding range of voltages developed in the secondary.

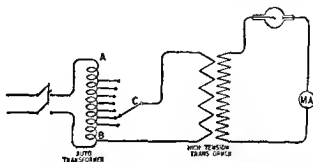


FIG 28 Connections for auto-transformer control of high tension voltage

Unlike the rheostat method, auto transformer control maintains a nearly constant tube voltage even when the tube current varies, because the potential difference between *B* and *C* depends on the position of *C* and is independent of current variations in the supply mains. This has both an advantage and a disadvantage. It is certainly an advantage to have the high tension voltage remain nearly constant in spite of changing loads, because, as we shall see later, the nature of the x-rays emitted by a tube depends on the tube voltage. On the other hand, if a short circuit develops, it is better not to have the high voltage maintained, and in this instance, rheostat control is to be preferred to auto transformer.

### PROBLEMS AND QUESTIONS

- 1 Describe, with simple diagrams, the two chief ways of controlling the voltage applied to an x ray tube
- 2 Make diagrams illustrating the control of voltage applied to an x ray tube, (i) by rheostat (ii) by autotransformer. Explain also why the rheostat acts as a kind of safety valve when a "short" develops in the tube circuit
- 3 How is the voltage across an x ray tube measured? Describe several means
- 4 Explain (i) why a voltmeter across the primary of an x ray transformer can be (and often is) marked to read secondary kilovolts, (ii) the objection to this practice

5 Explain fully the meaning of the following portion of the table placed over the control board of an x ray transformer

Primary Voltage	Autotransformer Button	Tube Voltage	
		10 ma	30 ma
80	3	77 kv	72 kv
90	8	88 kv	83 kv

Hence point out the objection to a prereading kilovoltmeter

6 Describe two ways in which a very high resistance can be used to measure the P D across an x ray tube

## CHAPTER IV

### CATHODE RAYS

In the original type of x ray tube a current passes through a rarefied gas, in the hot filament tube a current passes, although the vacuum may be nearly as perfect as modern means of exhaustion can make it. Before the action of either can be understood, it is necessary to consider somewhat in detail the whole question of the passage of electricity through a gas.

**31 Conductivity of Air** — Suppose an electroscope, made with the most perfect insulation possible, is given a charge. If the deflection of the leaf is observed hour after hour it will be found that, although there is an extremely slight falling of the leaf, the charge is retained even for days. We conclude, therefore, that while air is not a *perfect* insulator, at any rate it is an extremely poor conductor of electricity. (Evidence that air is not a perfect insulator has been given implicitly when it was pointed out that, once the voltage across two conductors exceeds a certain value, a spark jumps the gap between them.)

It is possible, however, to put air into a fairly good conducting state. A simple experiment will illustrate one means of doing so. Suppose a lighted match is held near the projecting end of a charged electroscope. It will be found that in a few seconds the leaf has fallen and the electroscope is discharged. The air in the neighborhood of the electroscope has had its conductivity enormously increased by the presence of the flame. In other words, the flame is what we call an *ionizing agent*, causing marked ionization of the air in its neighborhood.

Suppose we have an arrangement of apparatus similar to that illustrated in Fig. 29. In this case air from the neighborhood of a flame may be sucked through a tube *LM*, into which projects the top *K* of the insulated rod of a charged electroscope. With such an arrangement it will be found that as soon as the air from the flame is sucked along the pipe the electroscope begins to lose its charge. Evidently air in the conducting state can be carried from place to place.

Imagine next that the apparatus is altered so that the ionized air in its passage along the tube has to pass between two plates *P<sub>1</sub>* and *P<sub>2</sub>*, Fig. 30 which are joined, one to the positive, the other to the negative terminal of an

electrical machine or high voltage battery. It will now be found that, in spite of the suction through the tube, the electroscope *retains* its charge. In other words, the conducting air, after passing between the charged plates has lost its conductivity or is no longer ionized

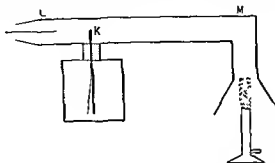


FIG 29 Ions from the neighborhood of flame when drawn along the tube discharge the electroscope

The removal of the conductivity by the charged plates (and many other experiments) proves that air is made a conductor because of the formation by the flame of small *electrified* particles. These particles, which we shall see presently may be either positive or negative, are called *ions*. Their existence

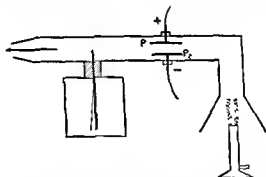


FIG 30 Ions drawn along the tube are removed by an electric field across the plates  $P_1$  and  $P_2$

provides a ready explanation of the discharge of the electroscope. If it is positively charged and ions are found near it, positive ions will be repelled, negative attracted. Each negative ion on reaching the insulated rod of the electroscope will annul some of the positive charge on it until finally the electroscope is completely discharged. Moreover, all the time the discharge is taking place *there is a stream of positive ions in one direction, negative in*

the pressure gets lower. The harder a gas x ray tube is, therefore, the greater the voltage necessary to maintain a given current through it. Conversely, the tube is said to be "soft" when the gas is in a fairly good conducting state.

**33 Appearance of Vacuum Tube** — The appearance of a vacuum tube when conducting a current at low pressures is very beautiful, and has certain general characteristics which it is well to note. Initially, or very shortly after the gas has become conducting a single sharp narrow streamer extends the length of the tube. As the pressure is reduced the band of light becomes wider and more and more diffuse until the whole tube is filled with luminosity. At still lower pressures (of the order of half a millimeter) the tube has a striking and very characteristic appearance. (1) Around the cathode is a thin luminous layer, *A* in Fig. 32, (2) next is a sharply defined dark space *B*, followed by, (3) another luminous region *C*, then (4) a second ill defined dark region *D*, and finally (5) a column of luminosity *E*, extending to the anode. At certain pressures this column is broken up into beautiful striations, that is, narrow regions alternately dark and light.

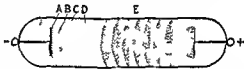


FIG. 32. Appearance of a vacuum tube carrying a discharge at a pressure in the neighborhood of one half a millimeter of mercury.

Most important of these regions is the sharply defined dark space, the Crookes' dark space, as it is called, or sometimes "the" dark space. With decreasing pressure, its width continues to increase, and is indeed a rough measure of the degree to which the tube has been exhausted. In the case of a gas x ray tube, the dark space should fill the whole tube. If, by any chance, an x ray tube presents the above appearance, that is, one with marked luminosity, the pressure is much too high and the tube must be re-exhausted before it is of any use. In the case of a hot filament tube, careless manipulation may result in the liberation of gas. If sufficient gas is present this will be evident by the general luminosity filling the tube when a high voltage is applied. Again re-exhaustion is the only remedy.

**34 Properties of Cathode Rays** — When exhaustion is extended beyond that giving rise to the above characteristic appearance, the dark space, as already noted, grows wider and wider until it finally fills practically the whole tube. This occurs when the pressure has now been reduced\* to about  $1/100$  mm, a value which is of the order of that in a gas x-ray tube. At

\* We speak of raising the vacuum when we lower the pressure.

this pressure a very faint beam of light proceeding *at right angles* to the cathode is frequently visible. Depending on conditions this beam may be narrow, covering only a small portion of the face of the cathode, or it may cover nearly the whole of it, it may be extremely faint or it may be well defined (Often it is quite visible in a "soft x ray bulb"). The direction of this beam, moreover, is independent of the position of the anode. For example, in a tube of the shape illustrated in Fig. 33 the beam is still at right angles to the cathode, although the anode is in an arm at one side of the tube.

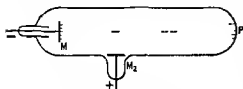


FIG. 33 Cathode rays leave the cathode normally

A second important appearance is characteristic of this stage. The walls of the tube, particularly at the end opposite the cathode, are seen to fluoresce with a glow, frequently greenish, whose color, however, depends on the composition of the glass. That the fluorescent light has some connection with the faint streamers is readily shown by simply bringing one pole of a magnet near the cathode end of the tube. Both the faint beam of light and the position of the fluorescent light at the other end move simultaneously.

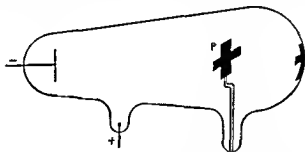


FIG. 34 A sharp shadow of the cross *P* is cast by a beam of cathode rays.

The name *cathode rays* has been given to the faint beam of light. What is their nature? Before answering this question it is desirable to look at some properties of the rays. From what has just been stated, cathode rays (1) are deflected from their path by a magnetic field, and (2) excite fluorescence where they strike the walls of a glass tube. (3) They travel in straight lines when no deflecting electric or magnetic fields are present. This is readily shown by using a tube of the kind illustrated in Fig. 34. With such a tube it is observed that if an obstacle *P* is placed in the path of the rays, a *sharp*

shadow is cast on the end of the tube, all the region around the shadow strongly fluorescing. This could be caused only by a beam which, like light rays, travels in straight lines. (4) Cathode rays represent a considerable amount of kinetic energy. This may be shown by using, not a plane cathode, as represented in Fig. 33, but a concave one. By this means the beam of rays (which it was pointed out above, proceed normally from the cathode) can be brought to a focus at a point, as illustrated in Fig. 35. If, now, a thin piece of metal be placed in a tube so that the spot to which the rays are focused is on the surface of the metal, in a short time incandescence will be observed in the neighborhood of the spot. On impact of the rays against the metal a large amount of heat is developed. (This point is of very great importance in connection with the action of either the gas or the hot filament tube.) (5) Cathode rays are deflected from their path by an electric as well as by a magnetic field. To show this a tube constructed as represented in Fig. 36 is used. By having a small cylindrical opening in the center of the anode, a narrow pencil of cathode rays may be obtained. This beam may

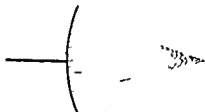


FIG. 35 Focusing of cathode rays.

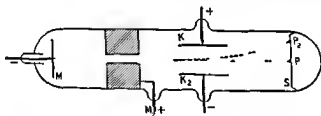


FIG. 36 Cathode rays are deflected by the electric field between the plates  $K_1$  and  $K_2$ .

be visible for only a short distance from the cathode, if indeed it can be seen at all; but, if at the far end of the tube, a fluorescent screen  $S$  be placed, the presence of the rays is at once evident by a round fluorescent spot at  $P_1$  on the screen. Suppose now, the tube has been constructed with two metal plates  $K_1$  and  $K_2$  and that these are joined one to the positive, the other to the negative terminal of a battery. It will then be found that the spot of light shifts from  $P_1$  to  $P_2$ . In their passage through the electric field between the plates, the rays have been deflected.

From this and the other properties enumerated, we conclude that cathode rays consist of a stream of electrified particles. Moreover, from the direction



of the deflection by the electric field, the charge they carry is at once seen to be *negative*.

**35 Nature of Cathode Rays** — The experiments which led to the discovery of these properties of cathode rays left no doubt about their corpuscular and electrical nature. Moreover, they provided the answer to questions which naturally arise concerning the size of the particles, their speed, and the magnitude of the charge they carry. A glance at Fig. 36 will show that it is a simple matter to measure on the screen  $S$  the distance from  $P_1$  to  $P_2$ , that is, to measure the amount the beam is deflected, and it should not be difficult to see that this depends on the very things we wish to know. To begin with, the greater the electric charge the particle has and the larger the voltage across the plates  $K_1$  and  $K_2$ , the greater the force pushing the particle to one

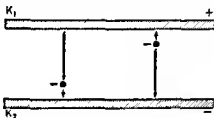


FIG. 37 The principle of Millikan's oil drop experiment. A drop, represented by the black dot, is pulled downwards by the force of gravity, upwards by the electric field between the plates  $K_1$  and  $K_2$ .

side. But heavy particles are not pushed aside as readily as light, nor fast particles as easily as slow, hence the amount of deflection depends not only on the force acting on a particle but also on its mass and its speed. For the trained physicist comparatively simple calculations connect all these factors together, and from his calculations and observations, made with both electric and magnetic fields, it can be shown that the value of  $\frac{e}{m}$ , that is, the ratio of the charge carried by a cathode ray to its mass, is equal to  $1.76 \times 10^8$  coulombs per gram.

As researches concerning the conduction of electricity through gases continued, it became evident that the charge carried by a cathode ray was a fundamental unit of electricity. It would be out of place or absurd to refer in detail to the pioneer investigations establishing this fact, and a brief reference is made to but one outstanding investigation, the famous oil drop experiment performed by Millikan. Like a few other famous experiments it is beautiful in its simplicity. By means of an atomizer, oil drops are sprayed in the space

between two charged plates, and the drops are then given a charge by ionizing the air in this region. A single drop ordinarily will fall slowly due to its weight but if it has a negative charge and the positive plate is above it, as in Fig. 37, the electric force acting on the drop will be in an upward direction, and may easily be adjusted until it exactly balances the downward pull of the earth. The drop will then be balanced in space, somewhat like Mahomet's coffin. Calculations based on this experiment enable the exact charge on the drop to be obtained and show that the charge is always equal to that on a cathode ray or to some multiple of it. Smaller amounts have never been observed and larger amounts occur in exact multiples of this fundamental unit of charge. The actual magnitude of the fundamental or electronic unit is  $4.80 \times 10^{-10}$  statcoulombs,\* or  $1.60 \times 10^{-19}$  coulombs\*.

From work in electrolysis we know that 96,490 coulombs is the charge carried by the ions contained in 1.008 gm of hydrogen, or

$$\frac{\text{charge on a hydrogen ion}}{\text{mass of a hydrogen ion}} = \frac{96490}{1.008} \text{ coulombs per gram,}$$

$$\text{or} \quad \frac{e'}{M} = 9.55 \times 10^4 \text{ coulombs per gram,}$$

where  $e'$  represents the charge on an hydrogen ion and  $M$  its mass.

Since experiment shows that  $e'$ , the charge on a cathode ray, is equal to  $e'$ , the charge on a hydrogen ion, it follows that  $M$  the mass of a hydrogen atom is about  $\frac{1.76 \times 10^6}{9.55 \times 10^4}$  or about 1838 times greater than  $m$  the mass of a cathode ray†. In passing we may note that the mass of a hydrogen atom is  $1.66 \times 10^{-24}$  gm, that of a slow cathode ray  $9.09 \times 10^{-28}$  gm.

In cathode rays then, we have to deal with particles of this small mass, all carrying the same negative charge of electricity. It is important to realize that the mass of a cathode ray is the same regardless of the nature of the materials in the cathode ray tube. The cathode may be made of iron, or of copper or of silver, or of aluminum, or any other metallic substance, the gas

\* It will be recalled that 1 statcoulomb is such a quantity of electricity that when placed 1 cm away from a similar quantity, with air as the medium between them, the force of repulsion between the charges is 1 dyne. It will be useful to remember, particularly when we discuss the question of x-ray dosage, that

1 coulomb or 1 ampere second =  $3 \times 10^9$  statcoulombs

† This is true only when the speed of the cathode rays is not great. Actually the mass is a function of the velocity, and at extremely high speeds the increase in mass becomes of great importance.

in the tube before it was evacuated may have been ordinary air, or oxygen, or hydrogen, or carbon dioxide, or any other kind — in all cases the same result is obtained. All slow cathode rays have this same mass. This was a startling discovery because it proved that there was a common constituent to all kinds of matter. The atom can no longer be considered uncut or uncuttable as it was throughout most of the nineteenth century. It must contain particles with a mass nearly two thousand times less than that of the hydrogen atom.

The speed of cathode rays depends on the potential difference between the cathode and the anode in the same way as the speed of a falling body depends on the height from which it has fallen, and may be thousands of miles per second. For example, for a potential difference of 10,000 volts, the speed is about 37,000 miles per second, or about one fifth of the velocity of light, for 100,000 volts, the speed is over 100,000 miles per second, and for a million volts, ninety-five per cent of the speed of light is obtained.

It is instructive to calculate the speed of a cathode ray for a given voltage. To do so the student must recall that unit potential difference exists between two points or two conductors, when unit amount of work is done in taking a unit charge from one point to the other, or when unit amount of energy is gained if the unit charge falls under unit potential difference. To be more specific, if unit potential difference, which for convenience we shall call 1 statvolt, exists between two conductors, and 1 statcoulomb falls through this potential difference, the energy gained is 1 erg, the fundamental unit of energy. Another important energy unit in common use is the *electron volt*. This is the amount of energy acquired when a particle having a charge equal to the fundamental or electronic unit falls through a potential difference of 1 volt.

It follows at once that, if the potential difference is  $V$  statvolts, and the charge is  $e$  statcoulombs, the energy gained is  $Ve$  ergs. Since the usual unit of potential difference is the volt, the student should remember that 300 volts = 1 statvolt, or that to change from volts to statvolts you must divide by 300.

Suppose, now, that a cathode ray (with charge  $4.80 \times 10^{-10}$  statcoulombs) falls through 10,000 volts. The energy\* it acquires

$$\begin{aligned} &= \frac{10,000}{300} \times 4.8 \times 10^{-10} \text{ ergs,} \\ &= 1.6 \times 10^{-8} \text{ ergs*} \end{aligned}$$

This energy appears as kinetic. Now the kinetic energy of a particle of mass

\* This amount of energy is more often described as 10,000 electron volts

$m$  grams moving with velocity  $v$  cm per sec is  $\frac{1}{2}mv^2$  ergs. In the case of the cathode ray we have seen that

$$m = 9.09 \times 10^{-28} \text{ gm}$$

Therefore, the kinetic energy of the particle

$$= \frac{1}{2} \times 9.09 \times 10^{-28} \times v^2 \text{ ergs}$$

Hence,

$$\frac{1}{2} \times 9.0 \times 10^{-28} \times v^2 = 1.6 \times 10^{-8}, \text{ from which}$$

$$v = 59.6 \times 10^4 \text{ cm per second}$$

$$= 37,100 \text{ miles per second}$$

**36 Structure of the Atom** — As we have just seen, the discovery of cathode rays showed that atoms of all elements must contain negatively charged particles, a conclusion which was amply confirmed by subsequent work. These particles we now call *electrons*, reserving the name cathode rays for electrons which are shot down evacuated tubes of the kind shown in Figs 33 and 34. Electrons may be released from atoms in a number of different ways. A very common method which we shall discuss more fully in Chapter VI consists in heating a metal to incandescence, in which case electrons evaporate

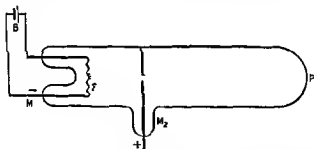


FIG. 38 A simple electron gun. Electrons are liberated from the heated filament  $F$

from the metal or, to be more scientific, there is a *thermionic emission* of electrons. In a radio tube, for example, the filament which you sometimes can see glowing, is heated to obtain a supply of electrons. If, therefore, an evacuated tube is made like the one shown in Fig 38, where the cathode of Fig 33 is replaced by a wire\*  $F$  heated to incandescence by passing an electric current through it, a beam of cathode rays is shot down the tube when the filament is joined to the negative terminal and the anode to the positive terminal of an

\* Frequently the wire is coated with a material like lime or calcium oxide which liberates electrons copiously when the wire is heated at a lower temperature than is necessary for the uncoated wire.

induction coil or any other source of direct voltage. Such an arrangement constitutes the essential features of what is sometimes called an *electron gun*.

The new atom which contains electrons must have a structure far from simple. Since an atom as a whole exhibits no electrical charge it must contain enough positive electricity to neutralize the negative on the electrons. What does it look like, and where is the positive electricity? Can we form a mental picture of it? The answer to these questions has not always been the same, but for a number of years it has been possible to visualize a model atom which has been extremely fruitful in explaining and interpreting many facts. This atom consists of a positively charged center or *nucleus* accounting for almost the whole of its mass, together with a number of electrons *whose total negative charge exactly equals the positive charge on the nucleus*. So small are both nucleus and electron that if an atom were enlarged to be the size of a balloon 60 feet in diameter, the nucleus and each electron would not be much bigger than a grain of sand. On this view the atom is a miniature solar system with the electrons revolving about the nucleus much as the planets revolve about the sun.

To distinguish one atom from another, two quantities must be known: (1) the *atomic weight* or the number proportional to the mass of the atom, (2) the *atomic number*. One or two concrete examples should make clear the meaning of atomic number. There is overwhelming evidence that in the atom of hydrogen, the lightest element, there is but one electron, with its unit negative charge, moving about the nucleus with an equivalent positive charge, in helium, the next lightest element, there are two electrons and the nucleus has two units of positive electricity, in lithium, the third lightest, there are three electrons and three positive unit charges on the nucleus, and, to give one other example, in the mercury atom, there are eighty electrons and the nucleus has eighty units of positive electricity. The atomic number is just the number of unit positive charges carried by the nucleus — which, of course, is the same thing as the number of electrons in the normal atom. Hydrogen, then, has an atomic number of 1, lithium of 2, helium of 3, and mercury of 80. In modern physics the atomic number is of even greater importance than the atomic weight because the chemical properties of an element depend on the number and arrangement of the electrons surrounding the nucleus, and this depends on the atomic number.

**37. Meaning of Ionization** — Since negative electricity attracts positive, each electron is strongly attracted by the nucleus. This electrostatic attraction provides the centripetal force necessary to keep the electron in orbital motion about the nucleus. If it were not for its motion, the electron would "fall into" the nucleus. By exerting a pull outwards, however, it is possible to remove

an electron completely out of the atom away from the attraction of the nucleus. When that has been done, the nucleus has one unit of positive electricity in excess of the amount necessary to neutralize the negative charge on the remaining electrons, and we have what is called a positive atom-ion, or more often, just a *positive ion*. Sometimes two electrons are removed from the atom, and we then have a doubly charged positive ion. The atom in each case is said to be *ionized*, and the means by which the electron or electrons have been removed are called ionizing agents. X-rays, gamma rays from radium, and, as we have already seen, flames are examples of such agents. The electron which has been removed from an atom does not always remain in solitary state, but frequently attracts to itself a neutral molecule or atom, or possibly several of them, forming a negative ion.

On this view electricity is never created, but is of the very essence of matter. When an ebonite rod is rubbed on wool, little forces (which we do not understand any too well) are brought into play which cause electrons to pass from the wool to the rod. For every million electrons gained by the rod, the wool loses a million. Consequently, whenever the rod acquires a million units of negative electricity, the wool, having a million positive units unbalanced by the electrons it has lost, acquires an equal positive charge.

A battery or a dynamo is not a means of creating electricity, but a device which separates positive from negative, with a resulting potential difference between its terminals. When a current flows in a circuit, it is simply a movement of electrical charges, — sometimes electrons only, sometimes negative ions in one direction, positive in the opposite.

**38 Ionization by Collision** — The ability to ionize a gas or a vapor through which it is passing is an important property of a rapidly moving electron. If moving quickly enough an electron may pass right through an atom leaving it unharmed, if moving very slowly, the electron may not have enough energy to do any damage, but over a wide range of speeds, it will remove electrons from many of the atoms which lie in its path. As we have seen, whenever an atom loses an electron it becomes a positive ion. Hence the path of a fast electron is marked by a trail of ions\*. This production of ions by a moving particle is one of the commonest ways of making a gas conducting. In the next two chapters we shall study this method of ionization in greater detail.

**39 Electron Bombardment** — Attention has already been directed to the fact that intense heat may be developed when electrons are suddenly stopped by a target. It is not surprising, therefore, that important effects may

\* See section 131

be brought about by controlled bombardment of certain materials by electrons or cathode rays

Special electron tubes have been constructed for the specific purpose of obtaining homogeneous beams of electrons with speeds corresponding to potential drops over voltages ranging from 1 to 15 kilovolts in the case of one tube, or from 10 to 100 kilovolts in another. Such tubes are convenient for a study of the effects of the electron bombardment of biological material.

Much faster electrons have been utilized in certain bombarding experiments, in which the cathode rays, after passing right through a thin sheet of metal in the wall of the cathode ray tube, emerge into the outside air. Tubes of this kind are sometimes called *Lenard Coolidge*, in honor of Lenard, a German physicist, and Coolidge, the present director of the General Electric Research Laboratory at Schenectady, N. Y. Lenard, in the last decade of the nineteenth century, made pioneer investigations relating to the passage of cathode rays through metallic foil. Coolidge followed up his work using potential differences exceeding a million volts to speed up the rays. Coolidge and other workers have shown that, under the action of these cathode rays outside the tube, yeast, ergosterol, and a few other substances produce vitamin D, that new species may be originated in plants and in animals, that changes in color may be brought about in glass and other substances, and that it is possible to distinguish natural from artificial sapphire by the difference in their response to the rays.

In an instrument called the *betatron* to which further reference will be made in Chapter XV, electrons are accelerated until they attain speeds the equivalent of a potential drop equal to or even exceeding 200 million volts.

**40 Origin of Roentgen Rays** — For the radiologist probably the most important use of cathode rays is to generate roentgen or x-rays. When cathode rays or high speed electrons are suddenly stopped by impinging against a hard metal target, the spot struck by the beam is the source of the invisible light called x-rays. Details concerning tubes used for this purpose, as well as concerning the properties of such tubes will be given in Chapter VI. Before doing so, it is desirable to consider further details concerning the passage of electricity through a rarefied gas.

## PROBLEMS AND QUESTIONS

1. Is air at atmospheric pressure a conductor of electricity? Describe several ways in which air may be made conducting.

2. Describe the variations in the conductivity of a tube with electrodes as the air is gradually removed, the electrodes being connected to high voltage terminals.

- 3 What are ions, electrons cathode rays?
- 4 Describe how the voltage across a tube (originally containing air at atmospheric pressure) varies as the air is gradually exhausted, if the tube is carrying a current
- 5 Describe the properties of cathode rays with reference to suitable experiments to illustrate these properties
- 6 What is meant by the atomic number of an element?
- 7 Explain, with the aid of a diagram, a method of generating a narrow beam of cathode rays
- 8 If a cathode ray has a charge of  $4.8 \times 10^{-10}$  statcoulomb, how many (i) electron volts, (ii) ergs, of kinetic energy does it acquire after falling through a P.D. equal to 1,000,000 volts? *Ans* (i)  $10^6$ , (ii)  $1.6 \times 10^{-6}$
- 9 Find the magnitude in ergs of an electron volt *Ans*  $1.6 \times 10^{-12}$ .



## CHAPTER V

### POSITIVE RAYS AND ISOTOPES

**41 Nature of Conductivity at Atmospheric Pressure** — In section 31 it was pointed out that even with the most perfect insulation available, an electroscope slowly loses its charge. It should now be evident that, if a few stray ions are at all times present in ordinary air, a ready explanation of this discharge may be given. As a matter of fact, a large number of investigations, many of them dating back to the beginning of this century, have shown conclusively that there is no doubt about the presence of such ions. If, then, an intense electric field is created between two conductors such as the knobs of a simple electrostatic machine or the secondary terminals of an induction coil, these ions, being charged particles, are acted on by a big force, and very quickly acquire a high velocity. If the field is intense enough, the ions have sufficient kinetic energy to ionize neutral atoms or molecules against which they collide. The ions and released electrons resulting from such collisions in their turn are speeded up by the electric field and very quickly they, too, ionize other atoms and molecules. In this way, once an electric field of sufficient intensity has been reached ionization increases so rapidly that a sudden discharge made evident by the crackling spark, takes place. In the case of corona, the field is intense enough to cause a discharge only within a limited region near the high potential conductor. If an earthed conductor should be brought too near, the corona will of course give way to a spark.

**42 Conductivity at Reduced Pressure** — When even a tolerably high voltage is applied to tubes of the kind illustrated in Figs. 31, 32 and 33 no discharge passes if the contained air is at atmospheric pressure, because the field between the electrodes is not sufficiently intense to enable the stray ions to acquire sufficient energy to ionize the neutral atoms or molecules with which they collide. When a partial vacuum is created, however, as we have already noted in section 32, there is a discharge in the tube. Because of the greater distance between individual molecules at the lower pressures, an ion now moves a greater distance without obstruction and so has a chance to acquire more energy before an impact takes place. A pressure is reached when the energy so acquired is sufficient to enable the ion to ionize on collision and there is a rapid accumulation of ions. A current passes positive ions moving towards

the cathode, negative ions and electrons towards the anode. If a stream of cathode rays is wanted, the vacuum is made so good that the liberated electrons, largely formed in the neighborhood of the cathode, move the full length of the tube with little obstruction. Figure 39 is an attempt to depict the state of affairs at somewhat higher pressures, when the tube is filled with light, as

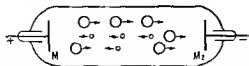


FIG 39 In a tube containing a little gas at not too low a pressure numerous positive and negative ions move in opposite directions

in an electric neon sign. At this stage there are numerous positive and negative ions.

**43 Positive Rays.**—The existence of a stream of positive ions may be shown very beautifully by using a tube in which holes are made in the cathode, not the anode, somewhat as shown in Fig 40. At suitable pressures, in *B*, the portion of the tube beyond the cathode, a narrow beam of light is seen as



FIG 40 A canal ray tube. Positive ions pass through the perforations in the cathode and at suitable pressures, give rise to colored canal ray streamers.

a continuation of each hole in the cathode, an observation made in 1886 by the German scientist Goldstein. At that date, it must be remembered, neither electrons nor ions had been discovered, and Goldstein, not knowing the true nature of the rays passing through the holes in the cathode, appropriately called them *canal rays*. It remained for

another German, Wien, in 1898, to show that canal rays, if made to travel through either an electric or a magnetic field, were deflected to one side, just like cathode rays, and so were electrified particles. There are three very important differences, however, between canal and cathode rays.

(1) The direction of the deflection of canal rays in a tube like the one shown in Fig 41, where a narrow beam passes between the electrified plates,  $K_1$  and  $K_2$ , is towards the negative plate, not away from it as in the case of cathode rays. Canal rays, therefore, must be positively charged. This, of course, is just what one should expect, for they are nothing but the stream of positive ions which come up to the cathode and pass through its perforation. In fact, J. J. Thomson, the famous English physicist who was one of the pioneer workers with these rays, changed their name to positive rays.

(2) It is much more difficult to deflect canal rays stronger electric and magnetic fields being necessary to do so. As a matter of fact Goldstein tried unsuccessfully to deflect them with a magnetic field. The reason for the difficulty in deflecting the rays is due to the much heavier mass of an ion than that of a cathode ray, because, as we pointed out when dealing with the deflection of cathode rays, the heavier a particle is the harder it is to push it out of its path.

(3) Measurements of the same kind as are used in cathode-ray deflection tubes show that canal rays are of atomic size but that their masses are not always the same. If the gas in the discharge tube is changed, the masses of the canal or positive rays are altered also. Again this is to be expected once we realize that positive rays originate in the positive ions in the discharge tube.

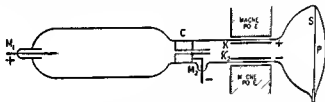


FIG. 41. A simple tube for the analysis of a beam of positive rays.

If a tube contains hydrogen, then ionized atoms of hydrogen will pass through the hole or holes in the cathode, if oxygen, then oxygen atom ions, and if there is a mixture of these two gases, in the canal ray beam there will be both oxygen and hydrogen ions.

**44 Chemical Analysis by Positive Rays** — If a positive ray beam containing a mixture of ions of different masses passes through an electric and a magnetic field, it will be sorted out into its components. This is the principle of the positive ray method of chemical analysis which was first used by J. J. Thomson with such remarkable consequences that it is necessary to understand it clearly. In the method originally used by Thomson a tube was built somewhat as shown in Fig. 41. The rays pass through a fine tunnel in the cathode *C* and on emergence travel across a highly evacuated region until they strike a screen *S* (or a photographic plate) at the end of the tube. When the screen is coated with certain materials there is a fluorescent spot of light at the place *P* struck by the rays, or if a photographic plate is used the rays affect it much as light does, and on development an image of the spot is obtained. In Fig. 42, an original photograph taken by Thomson, the spot at the lower center was caused by such a narrow beam of undeflected rays.

If, however, the beam passes between the electrified plates *A*<sub>1</sub> and *K*<sub>2</sub>, that

is, through an electric field, and at the same time, between the poles of a magnet, there is a sorting out of the rays or ions. When the fields are so arranged that one pushes the particles vertically, the other horizontally, then all particles of the same mass and same electric charge, regardless of their speed, strike the screen or the photographic plate along a curved line. It is much the same as if bullets of different sizes were emitted by a machine gun and on their way to a target were acted on by two forces, one pushing them

sideways, the other up or down. With such an arrangement all the bullets of one size would hit the target along one line, of another size along a different line, and so on. If a positive ray beam contains singly charged atoms of hydrogen, of oxygen, and of nitrogen there is a curved line on the plate corresponding to each kind of atom. In Fig 42 the beam which was analyzed in this way has given rise to four or five such curved lines, the line marked 1 arising from singly charged hydrogen atoms, that marked 2 from singly charged hydrogen molecules, which have double the mass since a molecule of hydrogen contains two atoms.



Courtesy Sir J. J. Thomson  
the Royal Society and Long-  
mans Green and Co

FIG 42 Positive Ray  
Analysis — Early  
Parabola Method  
showing hydrogen  
atoms and molecules

This method of analysis has many advantages. Only an extremely small amount of a substance is necessary to have its presence revealed in this way.

The method is even more sensitive than the spectro-

scope in detecting an element. It may reveal the existence of temporary, unstable groups of atoms which change into something else after the discharge is over. Moreover, on a single photograph a record is left of all the materials which take part in the discharge. A beautiful example of such a record taken by Harmsen, a German scientist, with an improved form of Thomson apparatus and reproduced through the kindness of Julius Springer, publisher of *Zeitschrift für Physik*, is shown in Fig 43.

It will be noted that opposite each line on this photograph a number is printed. These numbers give the masses of the corresponding particles on the usual atomic weight scale, and it is hoped that they will emphasize the biggest of all the advantages of positive ray analysis—the accurate comparison of atomic weights. For this purpose the relative displacements of different lines on the plate must be measured. This could be done with fair accuracy on Thomson's original curves, and, indeed, in his hands gave remarkable results, but an improvement in his apparatus was necessary for the exact measurements which modern science demands. Realizing this, Dr F W Aston, originally

a collaborator of Thomson, designed new arrangements which gave greater and greater accuracy and led to results of sufficient importance to win for him a Nobel prize. During recent years his work, supplemented by others, but notably by Bainbridge and by Dempster in the United States has been one of the most important lines of investigation in experimental physics.

In the forms of apparatus used by the modern experimenters the sorting out of the ions depends, as in the original arrangement, on a suitable combination

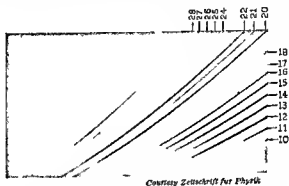


FIG 43 Positive Ray Analysis — Later Parabola Method. Note the isotopes of neon mass numbers 20 and 22.

of electric and magnetic deflecting fields, and the details of construction need not concern us. In the final photograph, however, we must note one difference. Short straight lines replace the long curves of the Thomson method. A typical photograph is shown in Fig 44.



FIG 44 Positive Ray Analysis — Modern Mass Spectrum, showing isotopes of cadmium.

Students familiar with photographs of optical spectra will note the similarity (See section 92). Just as a beam containing a mixture of different kinds of light on passing through a prism is spread out into a spectrum showing all its components, so the beam of positive rays by this method is separated into its constituents. It is not surprising that the apparatus used in the analysis is called a *mass spectrograph* and the photograph, in which each line corresponds to an ion of a definite mass, a *mass spectrum*. By measuring the separation of the lines along such a spectrum, an accurate comparison of masses and hence of atomic weights, may be made.

element argon, of atomic number 18. Elements with the same mass number but different atomic numbers are called *isobars*. For example, argon, atomic number 18, potassium, atomic number 19, and calcium, atomic number 20, all have isotopes of mass number 40.

#### 46. Determination of Atomic Weights by Physical Method —

If neon has two groups of atoms of mass numbers 20 and 22,\* what, it may be asked, is the atomic weight of this element? Can this result be reconciled with the atomic weight of 20.2 determined by chemical means? In chemical reactions the groups of isotopic atoms are not separated and the atomic weight determined chemically is an average value based on combining weights. To obtain the same average value from mass spectrograph data we must know the relative amounts of each isotope. This information is readily obtained from the degree of blackening of the mass spectrum lines on the photographic plate, because the larger the number of ions which strike the plate, the blacker or the denser the image. Neon photographs, for example, show that the 20 component is nine times more dense than the 22. It is just a matter of simple arithmetic to show that the average atomic weight is 20.2.

**47. Discovery of Deuterium** — The mass spectrograph, therefore, has provided a method of obtaining atomic weights *entirely independent of the old-established chemical means*. If both methods are reliable, values obtained by the two methods should agree. In 1929, the agreement was remarkable, the difference between corresponding values being only about 1 part in 10,000. In that year, however, it was shown that oxygen, which hitherto had been considered an element with only one isotope, of mass 16, had isotopes 17 and 18 present in small quantities. This meant that if the whole system of atomic weights is based on the assignment of 16.000 to the main isotope of oxygen, the average atomic weight of oxygen (the value based on all its isotopes) is slightly greater than 16.000, or conversely, if the *chemical determinations* of atomic weights are continued to be given in terms of 16.000 for oxygen, then the values for all other elements should be slightly less than those determined by the mass spectrograph method. The correction to be made is slight, but it was enough to indicate a disagreement between the atomic weights of hydrogen, as determined by the two methods, which was just greater than possible experimental errors. Birge and Menzel, American physicists, suggested that the lack of agreement might be due to an undetected isotope of hydrogen of mass number 2. Urey, Brickwedde, and Murphy, American scientists also, set out to look for such an isotope spectroscopically, and in 1932 announced

\* The most accurate results show that there is a faint third component of mass 21.

the discovery of heavy hydrogen or *deuterium* (symbol D) of mass number 2. In a tank of ordinary hydrogen there is only one part of the heavy variety to several thousands of the light, but after the original discovery of deuterium, means were soon found of increasing its concentration, and eventually of completely isolating it.

Had it been just another new isotope, there would have been nothing very startling about the discovery of deuterium. As it was, it created a stir in scientific circles the world over, and in a very short time gave rise to a wealth of researches in chemical and physical laboratories. The reason is not far to seek. In so far as the positive charge on the nucleus and the number of extra-nuclear electrons are concerned, two isotopic atoms are exact twins and cannot be distinguished by any differences in properties which depend on these factors. If the ratio of the nuclear masses is nearly unity, as in chlorine with its isotopes 35 and 37, it is only by refined means that very slight differences depending on this change of mass can be detected. When, however, the masses differ as much as they do in the two isotopes of hydrogen, that is, in the ratio of 1 to 2, differences in their properties are easy to detect. In both physics and chemistry, therefore, the discovery of heavy hydrogen was followed by hundreds of investigations, all seeking to find out differences in the properties of all sorts of compounds when ordinary hydrogen is replaced by deuterium.

Outstanding among these researches were those dealing with heavy water, the compound formed when deuterium unites with oxygen to form  $D_2O$ . You cannot distinguish the two kinds of water by looking at samples of each, but there are decided differences in their properties. For example, common water freezes at  $32^\circ F$  and boils at  $212^\circ F$ , whereas the corresponding temperatures for heavy water are  $38.8^\circ F$  and  $214.5^\circ F$ . Again, the vapor pressure of  $H_2O$  at  $212^\circ F$  is 760 mm Hg, but that of  $D_2O$  at the same temperature is only 721.6 mm.

**48 The Proton** — We have seen that the sorting out of positive rays has led to a physical method of determining atomic weights, to the discovery of the existence of isotopes in general, and of heavy hydrogen in particular. Of even greater importance for the development of physics is the use of the mass spectrograph for the accurate measurement of the masses of all isotopes, in terms of the number 16 0000 assigned to the main isotope of oxygen. Hitherto we have been using whole numbers, — the so called *mass numbers* 35 and 37 for chlorine, 1 and 2 for hydrogen, 20 and 22 for neon, 16, 17 and 18 for oxygen — as the values of atomic masses without any explicit reference to their exact values. Now with the improved modern instruments,

measurements of the displacement of the isotopic lines on a mass spectrum plate may be made to a high degree of accuracy. The results of such measurements show that in all cases, masses of isotopes are *very nearly* whole numbers. The few values given in Table V will illustrate the point.

TABLE V — A FEW EXACT VALUES OF ISOTOPIC MASSES IN TERMS OF OXYGEN 16 = 16.0000

Element	Mass Number	Mass
Hydrogen	1	1.00813
Deuterium	2	2.01472
Helium	4	4.00386
Lithium	6	6.01684
Lithium	7	7.01818
Beryllium	8	8.00765
Boron	10	10.01671
Boron	11	11.01295
Carbon	12	12.00386
Nitrogen	14	14.00756
Oxygen	16	16.0000
Neon	20	19.99896
Neon	27	26.9916
Aluminum	40	39.97564
Argon		

With the discovery of the "nearly whole number rule" for all isotopes, it was inevitable that the hydrogen atom, or more accurately, its nucleus called the *proton*, should be considered as an ultimate unit in the building of more complex atoms. At any rate, serious attention was given the theory that the nuclei of all atoms, in some way, are made of protons, with their positive charges, and negatively charged electrons. As we shall see later, this view is not now held, although the proton still remains as one of the fundamental particles in the formation of nuclei. Because of its importance in later work a brief further reference will now be made to the problem of isotopic separation.

**49. Separation of Isotopes** — In preceding sections we have learned how, by means of the mass spectrograph, the various isotopes of an element may be separated and their mass numbers evaluated. There remains the practical problem of so separating the isotopes that usable amounts of each variety can be collected.

During World War II this problem was of great importance in the years preceding the successful attempts to utilize nuclear energy arising from the fission of the element uranium, a question which will be considered in Chapter XVIII. Natural uranium has three isotopes, one of mass number 238, repre-



senting 99.3% of the whole, a second of mass number 235, to the extent of only 0.7%, and a third of mass number 234, which is present in such minute amounts that we can almost ignore it. For reasons which will appear later, it became highly desirable either to separate weighable amounts of the 235 kind or to increase the percentage of this isotope in a specimen of uranium. The magnitude of this problem, if even only a few grams of uranium 235 are to be collected, can be realized from the fact that Nier, an American physicist, using vapor from uranium bromide in a mass spectrograph, could collect less than a microgram of separated uranium 235 per 16 hour day.

In the successful separation of comparatively large amounts of individual isotopes of uranium and of other elements, use was made of several different methods, all of which had been known in principle before the uranium problem became urgent. A brief reference will be made to three of these.

(a) **Electromagnetic method — the calutron** — Somewhat similar in principle to the mass spectrograph, the calutron makes use of a beam of ions which, after being speeded up by an electric field, traverses a magnetic field powerful enough to cause the ions to move in circular paths. The reason for this deflection is explained in detail on page 265. Since the amount an ion is deflected by a magnetic field depends on its mass, an ionic beam containing a mixture of isotopes will give rise to different paths, one for each isotope, somewhat as shown in Fig. 45. Hence by suitably placing an obstacle with a narrow opening in it, a single isotope can be collected in a receiver placed beyond the opening.

In the successful use of this method for separating comparatively large amounts of uranium 235, use was made of the world's largest electromagnet, designed originally for a huge cyclotron at the University of California (see Chapter XV). The deflecting field of this magnet traverses a 6 foot gap between poles whose diameters exceed 15 feet.

(b) **Gaseous diffusion method** — This method is based on the fact that the rate at which a gas diffuses through very tiny openings depends on the mass of its molecules, being, in fact, inversely proportional to the square root of the mass. Hence, if we have a mixture of two isotopes of an element in the gaseous state, in a vessel with a wall containing very small openings — a *porous barrier* — the isotope of lighter mass will diffuse through the wall or barrier more rapidly than the heavier, and a partial separation of the two will result. It is interesting to note that Aston, in early attempts to separate the isotopes of neon, used clay piping as his barrier. The actual amount of separation resulting from diffusion through a single barrier is slight, and a cascade

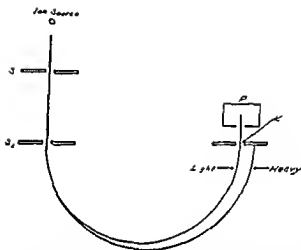


FIG. 45. A mixture of the ions of the two or more isotopes of an element, when speeded up by an electric field emerges from slit  $S_1$  each with its own momentum. In passing through a strong magnetic field, the ions are separated, each kind traversing a circular path slightly different from the others. By suitably placing a slit as at  $A$  in the figure any particular isotope may be collected. (Diagram from Smyth Report.)

uranium hexafluoride, and it had to have holes not larger than  $4 \times 10^{-3}$  inch. This and many other problems were successfully solved and, in 1945, after some years of hard, and at times discouraging, work, a satisfactory diffusion plant was operating at the Clinton Engineering Works in Tennessee.

In the actual collection of large amounts of uranium 235, a combination of the thermal diffusion method and the electromagnetic were used. By the diffusion method material with an increased percentage of uranium 235 was made, and then this "enriched feed material" was used in the calutron for the final separation.

(c) **The centrifuge** — This method employs the principle of the cream separator. If a system containing a mixture of two isotopes is rotated at very

high speeds, a partial separation is accomplished because the concentration of the lighter isotope increases near the axis of the rotating system, that of the heavier near the periphery. This method was also successfully used in the search for the release of nuclear energy, but it was not employed for any large scale production.

**50. Heavy Water.** — No explanation will be given of two or three other methods which have been used to some extent in the separation of isotopes but, before leaving the subject, a brief reference is made to the principle utilized in one method of manufacturing heavy water.

Shortly after the discovery of deuterium, the heavy isotope of hydrogen, it was found that, when ordinary water is decomposed by electrolysis into hydrogen and oxygen, the residual water left after a considerable amount of water has been decomposed contains a higher percentage of heavy water than it had originally. It then became obvious that, by collecting the residues from a number of electrolytic devices and decomposing the collected lot, now richer in the heavy variety, until the residue after the second stage was still further enriched, and by continuing such a process for several stages, heavy water of high concentration could finally be obtained.

### PROBLEMS AND QUESTIONS

- 1 Describe the construction and operation of a simple type of tube by means of which, by positive ray analysis, a beam of ions can be analyzed into its constituents. Explain fully.
- 2 An electron and a singly charged positive ion fall through equal potential differences. Compare (i) the energy, (ii) the velocity acquired by each.
- 3 Singly charged positive ions of ordinary hydrogen and of deuterium fall through equal potential differences. Compare (i) the energy, (ii) the velocity acquired by each.
- 4 Briefly describe two ways of separating stable isotopes of an element.
- 5 Indicate how the mass spectrograph can be used to compare atomic weights.
- 6 Explain how the atomic weight of an element like chlorine can be evaluated using the mass spectrograph.

## CHAPTER VI

### ROENTGEN TUBES

**51 Two Types of Tubes** — At the end of Chapter IV it was pointed out that x-rays originate when a beam of fast-moving electrons is suddenly stopped on striking a target of hard metal. To obtain a suitable beam of electrons two important methods have been used, with two corresponding types of x-ray tubes. In the first type, the gas tube, a residual vacuum is left at such a pressure that a well developed beam of cathode rays is projected from the cathode, while at the same time positive ions move toward this electrode. In the second type, the hot filament tube, electrons are emitted from a heated filament which also functions as the cathode of the tube. In this type the

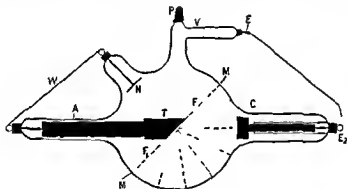


FIG. 46 A typical gas x ray tube

vacuum must be so good that there is *no cumulative ionization* by collision (section 38), or, in other words, so that there is no appreciable electron flow arising from this cause.

**52 The Gas Tube** — Although it would be difficult to find a modern radiology center where gas tubes are now in actual use,\* a brief reference will be made to this type in order to illustrate certain basic principles. The main features are illustrated in Fig. 46, where *C* is the cathode, with face concave

\* Special gas tubes such as one designed by Mueller are still used, particularly in connection with x ray spectrographs.

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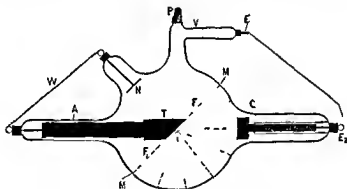


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\* Special gas tubes such as one designed by Mueller are still used particularly in connection with x ray spectrographs

or cup-shaped so that the cathode rays are brought to a focus on the face of the target. From the *focal spot* x rays spread out in all directions, passing through the whole half of the hemisphere in front of the plane  $MFM_1$ . Here it may be noted that when the current through a gas tube is in the right direction, the portion of the bulb in front of the plane  $MFM_1$  is usually strongly fluorescent, being separated from the remainder by a sharp line of demarcation. The target  $T$  forms the end of a long metal arm  $A$ , the anticathode, which by means of the connecting wire  $W$ , is in electrical contact with  $N$ , the anode. The anode  $N$  lies within a short side arm of the tube, and does not project into the main body of the tube.  $V$  is another side tube which carries a third electrode  $E$ , and is added for the purpose of regulating the gas pressure in the bulb.  $P$  represents a rubber tip covering the place at which the tube was sealed off from the exhaust pump after the initial exhaustion had been completed.

**53 Regulation of Current in Gas Tube** — It will be seen later that the nature of the beam of x-rays leaving a tube depends both on the current, that is, the milliamperage, and on the voltage across its terminals. An operator, therefore, must be able to control both the current and the voltage. Now, if the pressure of the residual gas remains constant, the higher the voltage applied to a tube, the greater the current through it. There are cases, however, where an operator may wish to change to a *higher* voltage without altering the milliamperage, or possibly with even a smaller milliamperage. How can this be done? To understand the answer to that question it is necessary to remember that the voltage required to maintain a given current through an ordinary vacuum tube varies with the pressure of the contained gas. (See section 32.) If, therefore, by any means the gas pressure in any x ray bulb is altered a different voltage will be required to pass the same current through it. If the vacuum is lowered (pressure increased), the resistance of the tube decreases or it becomes "softer." If the vacuum is raised, the tube runs "harder," that is, the resistance increases. A soft tube, therefore, is more conducting than a hard one\*. Putting it in another way, a higher voltage is necessary to maintain a certain milliamperage through a tube when it is hard than when it is soft. For a given tube, some regulation of the degree of vacuum may be obtained by the use of vacuum regulators. Because gas tubes are almost obsolete in x ray practice, details about such regulators are omitted, although it may not be amiss to point out that, by using the third

\* Later we shall see that the terms *hard* and *soft* are also used to describe the character of the rays leaving a tube.

electrode *E*, Fig 46, to pass a momentary current through the side arm *V*, small amounts of gas may be released from material packed in this arm and the pressure increased accordingly

**54 Blackening of Tubes** — With gas tubes, this slight increase in pressure is necessary, because with continued operation they are found to run harder, that is, the vacuum improves. The same improvement in vacuum occurs when a gas tube has been standing idle for some time. This gradual hardening is due largely to the absorption or adsorption of some of the residual gas by the walls and the electrodes of the tube. The adsorption is increased by the presence of a black metallic deposit which gradually forms on the inner walls of the tube — a deposit somewhat similar to that which may be observed on the walls of an old "clear glass" tungsten filament lamp. Besides increasing the rate at which the residual gas is adsorbed, the presence of blackening is objectionable, because it increases the resistance of the tube, it makes possible sparking along its walls, and it increases the danger of puncture.

TABLE VI

Metal	Atomic Weight	Atomic Number	Melting Point	Thermal Conductivity	Specific Heat	Volatilization Detectable at
Platinum	195.2	78	1750°C	0.17	0.3	1200°C.
Iridium	193.1	77	2290°C	0.17	0.3	1400°C
Osmium	190.9	76	2700°C	0.17	0.3	2300°C
Tungsten	184	74	3300°C	0.35	0.3	1800°C
Tantalum	181.5	73	2900°C	0.12	0.4	
Molybdenum	96	42	2500°C		0.7	
Copper	63.6	29	1084°C	0.92	0.9	
Nickel	58.7	28	1450°C	0.14	1.0	

Blackening is the result of two causes (1) the evaporation of hot metals, and (2) a cathodic disintegration known as *sputtering*. Sputtering consists of the ejection of metallic particles from the cathode. These particles, it is to be noted, are tiny pieces of metal and must not be confused with electrons. In a good tube, therefore, blackening is minimized by choosing a metal for the cathode which experiment has shown sputters a minimum amount (aluminum, for example) and by keeping the metal parts, particularly the target, as cool as possible, in order to prevent vaporization. We have already pointed out that a beam of cathode rays represents a considerable amount of energy and that at the focal spot where this energy is concentrated, enough heat may be developed to make a small hole in the face of the target. More-



over, if the metal does not actually melt, it may easily become so hot that marked vaporization takes place. Evidently it is desirable to choose for use as target a metal with a high melting point and to adopt some means of keeping it cool.

In this connection the information given in Table VI is of interest. It will be noted that platinum, which in the pioneer days of roentgenology was the metal used to the greatest extent as target, is by no means the most satisfactory. Compare it with tungsten, for example. Its melting point,  $1750^{\circ}\text{C}$ , is little more than half that of tungsten,  $3300^{\circ}\text{C}$ . Moreover, platinum is one of the metals which sputters readily, whereas tungsten sputters but little. For this reason, should any inverse current be present in the case of a platinum target tube, blackening would soon be pronounced. (During inverse the anticathode will act as cathode.) Tungsten, therefore, gradually replaced platinum, partly, perhaps largely, because of the research work of the General Electric Company, Schenectady, on the production of wrought tungsten.

**55 Methods of Cooling a Target** — To keep the target cool, use is made of several simple physical principles. In many gas tubes, the target at one time was just a "button" of tungsten set in the end of a massive piece of copper which served as a connecting conductor between the target and the external electrode. Now copper, it will be noted by a glance at Table VI, has both a high thermal conductivity and a high specific heat, and hence for both reasons, the temperature rises slowly.

Additional cooling is often brought about by attaching to the end of the anticathode (or anode) outside the tube, sheets of metal which because of their large surface are good radiators of heat. (See Fig 61 and Fig 67.) Cooling is also often accomplished by the use of water cooled targets, a very efficient method because circulating water continuously carries away the heat developed. Even if the water is not renewed by inlet and outlet pipes, its temperature cannot rise above  $100^{\circ}\text{C}$ , hence as long as there is water in the water cooler attached to the anode (see Fig 68 and Fig 69), high temperatures are not possible. Still another method consists in the use of an anode so massive that a large amount of heat is necessary to increase its temperature in appreciable amount. (See Fig 70.) As most of these cooling devices are employed in hot filament tubes, further reference to them will be postponed until this type of tube is under discussion.

**56 Thermionic Emission** — It has already been noted that in many hot filament tubes the vacuum is nearly as perfect as modern means of exhaus-

tion can make it. So high is the vacuum that if an attempt is made to use one as a gas tube, no current passes even with a very high voltage across the tube. How, then, does it operate? To answer that question, it is necessary to explain in greater detail the subject of thermionic emission of electrons, to which a brief reference was made in section 36. This can best be done by reference to one or two simple experiments. Figure 47 represents a highly exhausted glass bulb provided with three electrodes or terminals, 3 joined to an inner sheet of metal *P* which we shall call the plate, 1 and 2 to the ends of a filament *F* of fine wire, tungsten, for example. Terminals 1 and 2 are connected to a storage battery by means of which current may flow through the

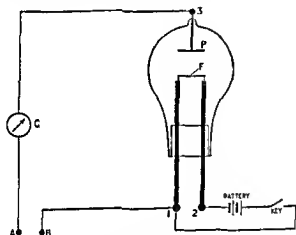


FIG. 47 A thermionic current flows across the highly evacuated tube, when the filament *F* is hot and is negative

filament and heat it to incandescence. A second circuit including a galvanometer *G* or a milliammeter is made by joining the 110 D.C. terminals *A* and *B* to 1 and 3 as illustrated in the figure. A deflection of *G* will then indicate a current flowing around the circuit *A* to *G* to 3 to plate to filament to 1 to *B*. Is there any such current? We distinguish two cases. (1) With filament cold, that is, key open, it is found that, no matter what the polarity of *A* and *B* is, no current is indicated by *G*. (2) With the filament incandescent (key closed), however, if *B* is negative, a marked current is indicated, whereas if *B* is positive, no current passes.

Evidently, therefore, a current passes through such a tube when the filament is hot and when it is negative. Now, what is the explanation? It is found in the fact that any hot piece of metal is a source of electrons. At the surface

of metals a process somewhat akin to evaporation goes on, as a result of which, at high temperatures, there is a copious emission of electrons known as a *thermionic emission*. In the above tube, therefore, the hot filament liberates electrons, if the filament is negative, and the plate positive, since negative repels and positive attracts negative electricity, these electrons are driven across the vacuum space. There is, therefore, a current of electricity which, in this case, consists of a stream of negatively charged electrons. If the filament is positive, however, because of the attraction of positive for negative, the electrons cannot escape from the filament and no such current exists.

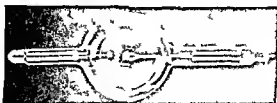
It is well to note that, although the electrons move from the filament to the positive plate, the direction of the current is from plate to filament. This is because of the convention that current direction is that in which positive electricity moves. Negative electrons coming out of a conductor is equivalent to positive electricity flowing into it.

**57 Hot Filament Rectifiers** — It should now be evident that if the supply voltage is 110 *alternating*, a stream of electrons will cross the tube only during the half cycle when the filament is negative. In other words, an intermittent but unidirectional current flows in the circuit containing *G*, although an alternating voltage is applied. A tube of this sort, frequently called a *diode*, therefore, is an excellent rectifier and has many practical applications. For example, in high tens on circuits, rectifying valves embodying this principle have practically replaced the mechanical rectifier discussed in section 19. In the next chapter details concerning this method will be given.

**58 Hot Filament X-Ray Tube** — Dr W D Coolidge, of the General Electric Research Laboratory, was the first scientist to construct an x-ray tube of the hot filament type. A tube of this kind differs from the gas tube, not because x-rays originate in any different manner, but because the stream of high speed electrons has its origin in an incandescent filament. Although there are many varieties of hot filament tubes, certain fundamental principles are utilized in nearly all of them, and these the student should clearly understand.

To begin with, we cannot do better than examine the construction and operation of the Universal Coolidge tube, one so satisfactory that, after many years of service, it is still on the market in only slightly altered form. Figure 48 is an actual photograph. This type, like almost any other, consists essentially of a filament *F*, Fig 49, which acts also as the cathode, and the anode *A*. To heat the filament, an independent circuit, called the *filament circuit*,

is necessary. In the original arrangement a storage battery  $B_1$  and  $B_2$  was used as the source of supply for the circuit. In the arrangement in actual use, as shown in Fig. 50, a branch from the A.C. mains supplies a small filament step-down transformer, the secondary of which is connected in series



*Courtesy General Electric X-ray Corporation*

FIG. 48 The Coolidge Universal Hot Filament X-ray Tube.

with the filament. While this arrangement is more convenient it has one disadvantage. Voltage fluctuations on the line will cause corresponding fluctuations in the filament and consequently, as we shall see later, alter the milliamperage through the tube.

To give the necessary high speed to the liberated electrons the high tension voltage is applied to the tube in the usual way, the hot filament being, of

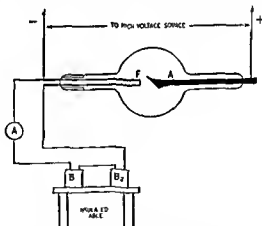


FIG. 49 Simple connections when filament of a hot filament x-ray tube is heated by means of a storage battery

course, negative. Since the whole filament circuit is raised to the high potential of the cathode, it is necessary to insulate the storage battery (or the filament transformer). The complete circuit therefore, includes (1) the usual high tension circuit, (2) the filament circuit. In Fig. 51 connections

## ROENTGEN TUBES

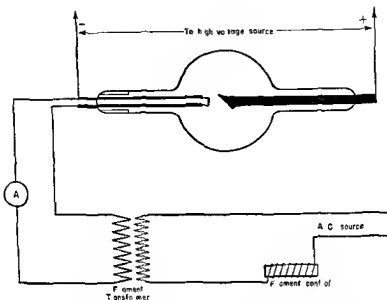


FIG 50 Simple connections when filament is heated by a step down transformer

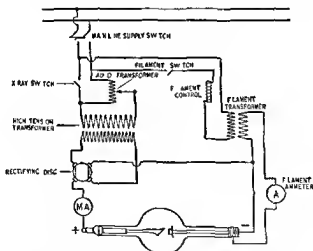


FIG 51 Complete connections when a hot filament tube is operated with high tension voltage controlled by autotransformer and rectified by mechanical rectifier

for the complete arrangement with mechanical rectifier (minus the synchronous motor circuit) are shown (In the next chapter diagrams of circuits using rectifying valves will be given) It will be seen that the high tension circuit, which in this case has autotransformer control, is exactly the same as that already discussed. The new feature is the filament circuit controlled by the filament switch and containing an ammeter to enable an operator to read the current heating the filament. By means of the filament control (1

rays or electrons strike. In the gas x-ray tube, the beam is focused on this spot partly because of the shape of the cathode, partly because the walls of the tube in the neighborhood acquire a negative charge and this charge exerts a repulsive effect on the beam of electrons. In hot filament tubes focusing is brought about partly because the electric field which exists between cathode

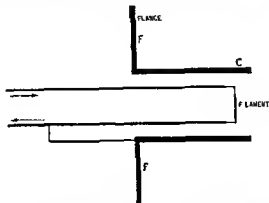
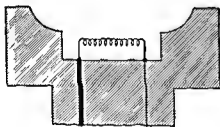


FIG. 52 Focusing device in the universal Coolidge Tube

and anode directs the beam of electrons towards the target, but more so because of the actual structure of the cathode itself. In the universal tube, for example, the filament, wrapped into a small flat spiral, is surrounded by a concentric metal cylinder, one end of which projects a little beyond the filament, as shown in Fig. 52. The other end is attached to the flange *F*.



Courtesy Philips Gloeilampenfabrieken, Holland

FIG. 53 A focusing arrangement in a hot filament tube



Courtesy General Electric X-ray Corporation

FIG. 54 A close up view of filaments in a double filament tube.

As the cylinder and flange, and the filament itself are all in electrical contact with the negative high tension terminal, a repulsive force acts on the liberated electrons. A somewhat similar arrangement is shown in Fig. 53, a diagram taken from literature of the Philips' X-ray works. Figure 54 is a close-up photograph showing the actual relation of the filaments, in a special double-

filament tube, to the surroundings. By using filaments of different shapes and adjusting the relative position of the parts, focal spots of different sizes are obtained.

"The focal spot size, shape, and distribution can be controlled almost entirely by the filament size, shape and position relative to the rest of the cathode structure" (Gross and Adlee)

**61. The Anode and Target** — In the universal tube, the anode head is of solid tungsten, whose inclined face forms the target, as shown in Fig. 48. No cooling device is added, it being possible to operate the tube with the anode white hot, provided unidirectional voltage is applied.

In later sections reference will be made to tubes of other design.

**62. Control of Tube Current** — In the gas tube we have seen that the residual gas is conducting, the current consisting of a stream of positive ions

TABLE VIII — FILAMENT CURRENT  
3.6 AMP

Kilovolts	Mill amperes
3	2.0
8	4.0
15	6.0
30	7.8
40	8.8
58	9.7
90	9.8
110	10.0
130	10.0
165	10.5

TABLE IX — FILAMENT CURRENT  
3.5 AMP

Kilovolts	Mill amperes
5	2.0
10	2.5
20	3.7
25	4.0
60	4.2
80	4.3
108	4.4
130	5.0
150	5.0
160	5.2

in one direction, along with cathode rays in the opposite direction. In the hot filament tube the current consists solely of the stream of negative electrons liberated from the filament. How is the magnitude of this current controlled? In order to understand the answer to that question it is well to recall that an electric current is measured by the total quantity of electricity passing each second any "point" on the circuit. If, therefore, more electrons are transferred every second from the filament to the target, the tube current will be greater. Now work on thermionic emission has shown that the higher the temperature of the hot filament the greater the supply of electrons. *The milliamperage through the tube, therefore, can be increased simply by increasing the filament heating current.* But, it is asked, where does voltage come in? That can be answered with reference to experimental results such as

given in Tables VIII and IX (taken from General Electric Co. literature). The numbers in Table VIII refer to a tube whose filament current was kept constant at 3.6 amperes.

Greater and greater voltages were applied to the tube, and for each value the corresponding tube current was measured. It will be noticed that, while at first the tube current increases with increasing voltage, a stage is reached at which increase in voltage produces slight increase in milliamperage. Those who prefer to study results in graphs rather than in tables will see that Curve A, Fig. 55, shows the same result even more clearly. In Table IX and Curve B, Fig. 55, the same result is shown for a different filament current, the only

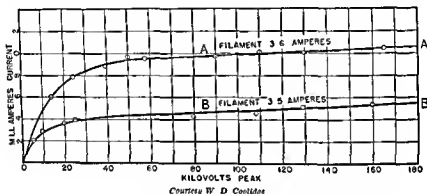


FIG. 55. Graphs showing saturation tube current for two different filament currents.

difference in the two cases being that the maximum tube current in the latter is greater. Experiment tells us, then, that *corresponding to each filament current, there is a maximum value of the tube current, which is independent of the applied voltage*. The explanation of this maximum current — called the *saturation current* — is simple enough. The available supply of electrons from a hot filament depends on its temperature and therefore on the magnitude of the filament current. Evidently no more electrons can be transported across the tube per second than are liberated each second from the filament.

The student may wonder why all the liberated electrons should not be transported to the anode at low as well as at high voltages. The chief reason for this lies in the existence of what is called the *space charge*. Suppose a filament is heated *without* the application of a potential difference between filament and anode. The evaporated electrons then form a cloud of negative electricity in the space immediately surrounding the filament. Since negative electricity repels negative, due to this space charge there is a strong repulsive force which not only prevents the emission of further electrons but also



drives electrons back into the filament. When a comparatively small voltage is applied across the electrodes (with anode positive), the electrons move to the anode and a current is recorded. But with low voltages the speed of the electrons is not great, and they are present in sufficient numbers in the region between the electrodes to continue to exert a backward force on those electrons near the filament. For a given field between the electrodes and a fixed filament temperature, a balance is reached when electrons are emitted from the filament at such a rate that the force on those near the filament due to the space charge cancels the applied electric field.

As higher and higher voltages are applied, a greater and greater number of electrons is transported each second across the tube until ultimately all the electrons emitted by the filament reach the anode. As already noted we have then the saturation current. Hot filament x ray tubes may therefore be designed so that control of the tube current is exercised in two ways: (a) by total emission of electrons from the heated filament, (b) by the utilization of space charge. If the applied voltage is sufficiently high to ensure saturation current, the tube current depends only on the temperature of the filament, that is, on the total electron emission. In this case the tube current is readily altered by changing the filament current, whose magnitude is read off the ammeter in the filament circuit. It is, then, highly desirable that the operator of a particular tube should know the tube (saturation) current corresponding to each ammeter reading. Such information he can readily obtain for himself by taking, for each of several filament current values, the saturation tube current. He will then have a table similar to Table X (a copy of some actual results taken from an early paper by Dr W. D. Coolidge).

By plotting these results an extremely useful curve similar to that in Fig. 56 will be obtained. Figure 57 is a copy of a similar curve for a Universal tube taken from advertising literature.

When a tube current is controlled by a space charge, it must be operated on the curved part of the graphs reproduced in Fig. 55. In other words, the fila-

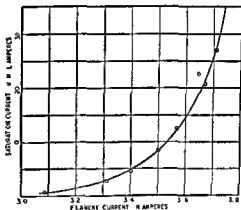


FIG. 56 Graph showing how the saturation tube current varies with the filament current

ment temperature must be sufficiently high that, within the range of voltages utilized, saturation current is never attained

TABLE X

Filament Current	Tube Current
3.09 amp	0.6 ma
3.31	2.5
3.40	4.4
3.50	8.2
3.57	12.6
3.67	20.7
3.65	21.8
3.71	27.0
4.13	35.4

Although in emission control an increase in voltage beyond the value necessary to produce saturation does not alter the magnitude of the tube current, it does alter the nature of the beam of x-rays (See section 110) Moreover, an increase in voltage beyond this point means an increase in the electrical power supplied the tube. Care should be exercised, therefore, not to exceed the maximum voltage and maximum power which is safe to use with a particular tube (See section 67)

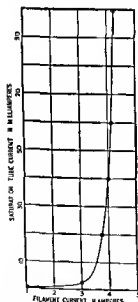


FIG 57 Graph showing that a slight change in filament current may cause a marked change in tube current

**63 Voltage Stabilizer** — In connection with the relation between filament current and tube current it is important to note that a very slight change in the filament current may produce a big change in the tube current. If we take some actual numbers from the curve of Fig 57, we see that with filament current 4 amperes, the tube current is 40 ma, while an increase to  $4\frac{1}{4}$  amperes raises the tube current to 100 ma. This has an important practical aspect. Should the filament current fluctuate, there will be marked changes in the tube current — as much as a 25 per cent change for a 1 per cent change in filament current. Obviously this is not desirable.

If storage batteries are used as the source of supply for the filament circuit, voltage fluctuations are negligible. Unfortunately, however, storage batteries are not so convenient as a filament transformer, and the latter is almost entirely used. The supply for

the transformer is commercial A C, and in this case voltage fluctuations are inevitable. Most readers will have observed a sudden dimming of incandescent lights when, perhaps in another part of the house, an electric iron or toaster is turned on. The voltage applied to the lamps has lowered because of the greater "load" put on. Now, such sudden changes in voltages are almost inevitable when working with a supply used for many purposes and in many places. In using a hot filament tube with filament transformer, therefore, and with no special means for getting rid of voltage fluctuations, marked changes in milliamperage may occur.

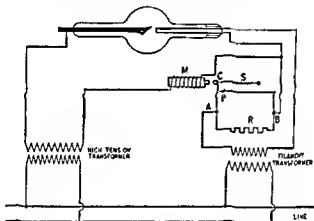


FIG. 58 To illustrate the operation of the Kearsley Stabilizer

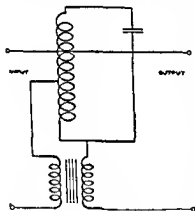
By means of a voltage stabilizer, however, it is possible to maintain a constant tube current in spite of voltage fluctuations.

The student will understand that any arrangement in which resistance or impedance increases (or decreases) in step with an increase (or decrease) in voltage will maintain a constant current in any ordinary circuit. For example, there is a type of lamp (using iron wire in an atmosphere of hydrogen) which gives the same current for a wide range of applied voltages. This is because the resistance of the lamp increases with rise in temperature and hence with an increase in the power supplied. In this special lamp the increase in resistance just compensates for the increase in voltage. This principle of adding resistance when the voltage goes up, is utilized in the *Kearsley Stabilizer*.

This stabilizer, designed by Kearsley of the General Electric, makes use of a mechanical device which automatically throws more resistance in the filament circuit when the voltage rises and cuts out resistance when the voltage drops. The stabilizer in actual use is not quite so simple as that shown in

Fig 58, but this diagram will make clear its basic principle. It will be noted that the filament circuit includes the secondary of the filament transformer, the filament itself, and a resistance  $R$  in parallel with a branch  $APB$  of very low resistance. This branch circuit is sometimes open, sometimes closed, because it contains an interrupter, similar to the hammer break of an induction coil, controlled by the electromagnet  $M$  in the high tension tube circuit. When a tube current is flowing,  $M$  is magnetized, the soft iron piece  $G$  is attracted, and the contact at  $P$  is broken *provided* the pull on  $G$  is great enough to overcome the tension of the controlling spring  $S$ . The greater the tension of this spring, the greater the tube current necessary to separate the contacts, or, for fixed tension, the farther away the electromagnet, the greater the tube current.

Considering now the filament circuit as a whole, we see that it has two possible resistance values: (1) a high value, when the contact at  $P$  is open and the resistance  $R$  is the only path between  $A$  and  $B$ , and (2) a low value, when the contact is closed, and  $R$  is shunted by a very low resistance. In actual use, when the electromagnet and the spring are set for a desired tube current, and the circuits are closed, the interrupter is in a state of rapid vibration, the resistance of the filament circuit alternating between the high and the low values. There is then a resultant average value for the net resistance and hence with steady applied voltage, both filament and tube currents remain constant. If the line voltage suddenly increases, the milliamperage through the tube does not increase because the high resistance  $R$  is thrown in for a longer portion of the total time and so the average filament resistance increases, thus compensating for the rise in voltage. On the other hand, if the voltage drops, the contact points at  $P$  remain closed for a



Courtesy General Electric X-ray Corporation

FIG 59 To illustrate the principle of a constant voltage stabilizer. For a 12 per cent variation in voltage on the input side the output voltage varies only 1 per cent.

longer fraction of the time, the average filament resistance becomes less, and once more the tube current remains constant.

The Kearsley stabilizer, it will be noted, maintains a constant tube current by automatic control of the filament current. The *constant voltage stabilizer*, another type which in some respects is more suitable for the type of x-ray apparatus now on the market is so designed that, when a fluctuating line

voltage is applied to the input side of the stabilizer, an almost steady voltage can be taken off the output side. A good stabilizer of this kind shows a variation of only 1 per cent in the output voltage when the input fluctuates as much as 12 per cent. It is not easy for anyone not trained in electrical engineering to understand fully the operation of this type of stabilizer, but the diagram in Fig 59 will give a general idea of the arrangement used. For this diagram the author is indebted to Mr W C Baldwin, manager of the Engineering Service of the General Electric X ray Corporation. Mr Baldwin states that their product, "The Universal Stabilizer, as most other stabilizers basically consists of a saturated core reactor and an air gap reactor run well below saturation."

**64 X-Ray Protection and Metalix Tube** — Although a detailed discussion of the properties of  $x$ -rays has not yet been given, probably all medical students are aware that unwanted  $x$ -rays falling on the body of either patient or operator may have serious injurious effects. It is very necessary, therefore, to provide adequate protection against such rays. To do this many precautions must be taken (see section 113), but obviously the first step is to see that, if possible, the beam of rays leaving the tube is restricted to a

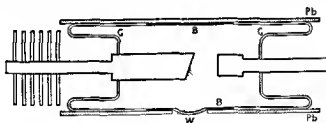
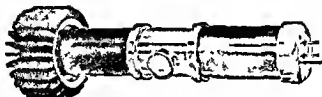


FIG 60 Schematic diagram of metalix x ray tube

narrow bundle. To some extent this can be accomplished by surrounding the bowl of the tube with some material which absorbs all or nearly all the rays which strike it. An opening, of course, must be left to allow the passage of the useful cone of rays. Some of the earlier tubes were so covered with a protecting covering of rubber impregnated with lead oxide, lead being an excellent absorbing material for ordinary  $x$  rays, or with a protecting bowl of thick lead glass.

A radical departure in  $x$  ray tube protection and in tube design was embodied in the so-called *metalix* tube, first put on the market by the Philips' Gloeilampenfabrieken X-ray Works Holland. Although Coolidge, as early as 1915,

had experimented with a metal tube, the metalix was the first which used the principle of metallic protection in the tube itself, to be put in the hands of radiologists. The main features of this type will be understood by a study of Fig 60 and Fig 61 which shows its general appearance. The tube consists essentially of a cylinder of chromium-iron alloy, *B*, in Fig 60, which at each end is sealed to the re-entrant glass cylinders *G, G*. A window *W* placed opposite the target permits the passage of all but the softest x-rays. The protection provided by the central metal cylinder is greatly increased by a layer of lead which surrounds it. In addition, the somewhat massive anode and the cathode assist in cutting off unwanted rays, particularly longitudinally,



Courtesy of Philips Glühlampenfabriken X-ray Works

FIG 61 The Metalix x ray tube

and a layer of bakelite, which forms the casing of the whole tube, adds more protection. At the same time this casing shields the bright light of the incandescent filament and mechanically is a protection to the glass.

The General Electric X ray Corporation have a tube, somewhat similar in appearance, in which an all glass cylindrical envelope is surrounded by a removable casing, providing both protection and insulation.

**65 Line Focus** — The metalix tube introduced another new feature in x-ray tubes, and that was the use of a linear instead of a circular spot, a suggestion originally made by Goltze. To understand the significance of this change, the student must be clear about two points. The first has to do with the intense local heating generated at the focal spot. (Recall section 55.) Concerning this it should be evident that the *larger* the area over which this heat is developed, that is, the larger the focal spot, the lower the resulting temperature and the less the danger of destroying the tube. The second point concerns the relation of the size of the focal spot to the sharpness of the picture when the shadow of an object is observed on a fluorescent screen or a photographic plate. If the student will think of x-rays as invisible light (as indeed they are), he will realize that the *smaller* the dimensions of the source of the beam the sharper the shadow picture of an object, *unless it is a flat one placed*

close to the screen or plate. Figure 62, which illustrates the point, will be very familiar to anyone who has taken a course in elementary light. For sharp detail, therefore, the focal spot should be as small as possible.

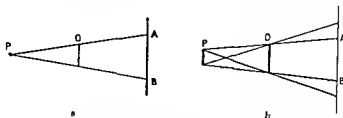


FIG 62 In (a) the small source of light  $P$  casts a sharp shadow of the obstacle  $O$ , in (b) the broad source gives rise to the deep shadow  $AB$  surrounded by a penumbra.

But if the focal spot is very small, the power input (the "load" on the tube) must be kept small because of the temperature effect, and frequently it is not desirable to restrict the power. For example, the smaller the power, the longer the exposure when x-ray photographs are made, and in many cases it is necessary to have short exposures.

Designers of x-ray tubes, therefore, were faced with the problem of combining sharp shadows with short exposures, or in other words, of retaining the equivalent of small focal spots with adequate power input. The problem was solved in two ways, (1) by the use of a *line* focal spot, as in the metalix tube, and (2) by the use of a rotating anode (see section 66).

In the metalix tube, and many others since placed on the market, a linear filament is so placed in relation to the surrounding cathode that a focal spot of the shape  $AB$ , Fig 63a, is formed on the face of the target  $TT'$ , this face being inclined to the axis of the tube at an angle of  $71^\circ$ , not the  $45^\circ$  previously used

with circular spots. Now, although the actual length of the focal spot is several times its width, to an observer looking along the central part of the beam of x-rays, its *effective* length, in so far as its ability to cast shadows is concerned, is only  $CD$ . Thus, although the actual total area of the spot is as illustrated in Fig 63b, its effective "shadow-casting" area is more like Fig 63c. Because of the greater actual area, it is possible to use an electric load on

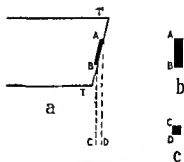


FIG 63  $AB$  represents the actual area of the focal spot,  $CD$  the projected area looking along the dotted lines.

the tube considerably greater than when a spot of actual area Fig 63c is formed on a  $45^\circ$  face target

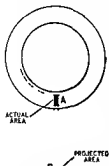


FIG 64 The heavy circles represent the bevelled edge of a rotating anode *A* being the actual area of the focal spot

**66 Rotating Anode** — To permit the use of still higher amounts of power, tubes with revolving anodes have been designed by the Philips' X-ray Works, the General Electric X-ray Corporation, Machlett Laboratories and others. In tubes of this kind, although the focal spot is stationary and of the rectangular shape shown by the black spot *A* in Fig 64, because the anode is kept in rotation, the area over which heat is developed is the annular space shown in this figure by the dotted circles. In the General Electric tube illustrated in Fig 65 and Fig 66, a disc of tungsten is rotated at a speed of 3000 r p m by an induction motor whose stator is outside the evacuated part of the tube. The electron beam strikes the beveled edge of this disc, clearly shown in Fig 65, giving rise (along the center of the useful beam of rays) to an *effective* spot which, in one tube, is 2 mm  $\times$  2 mm when

the actual area over which heat is produced is 7 mm (the length of the actual spot)  $\times$  190 mm (the mean circumference of the annular area). With such a tube, therefore, high power inputs are possible without losing the advantages of a small focal spot. For example, with a certain tube of this type, with an



Courtesy General Electric X-ray Corporation

FIG 65 A rotating anode tube

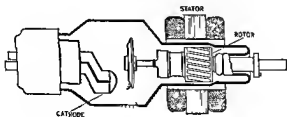
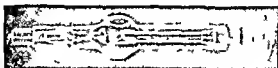


FIG 66 Diagram showing the essential features of a rotating anode tube



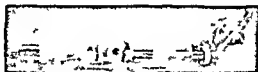
effective focal area as small as  $1 \text{ mm} \times 1 \text{ mm}$ , it is possible to use the same power input and same exposure time as for an effective spot of  $3.8 \text{ mm} \times 3.8 \text{ mm}$  with a stationary anode

✓67. Rating — From the preceding sections, it should be evident that it is highly desirable to know the maximum power which may safely be supplied



Courtesy General Electric X-ray Corporation

FIG 67 A radiator x ray tube



Courtesy Philips Gloeilampenfabrieken X-ray Works

FIG 68 A water cooled x ray tube



Courtesy General Electric X-ray Corporation

FIG 69 A water cooled x ray tube

to a tube, as well as the time this or any lesser amount may be used. This is what is meant by *rating*.

In considering this question the student should realize that only a very small fraction of the total energy supplied a tube goes into the energy of the x ray beam. The remainder, which goes into heat, is a "dead loss," and, as we have already pointed out in section 55, steps must be taken to remove that heat sufficiently rapidly to prevent injury to the tube. In that section reference has been made to most of the ways in which rapid rise in temperature is prevented. Note again Figs 61 and 67, in which the tubes are equipped with radiator fins to dissipate the heat conducted along the anode, and Figs 68 and 69 illustrating tubes provided with water cooling. Note, also Fig 70,

## ROENTGEN TUBES

which shows clearly a massive blackened cooling sphere at the end of an anode which itself has a high thermal capacity. The student will recall that black bodies are good radiators, and that the higher the thermal capacity of a substance, the lower the temperature rise for a fixed amount of heat.

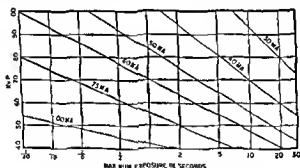
The actual quantity of heat developed is directly proportional to the total energy put into the tube and that, it will be remembered, depends on the



Courtesy Philips Gloedbuizenfabriek, X ray life 12

FIG 70 An x ray tube with a massive anode and blackened cooling sphere

product voltage  $\times$  current  $\times$  time (Recall  $VIt$  joules in ordinary circuits). If, then, a radiologist is told that a certain tube can be safely operated for 30 seconds, at 85 kilovolts peak (Kv P) with a current of 30 ma, he has a rating which is simple and definite. But it does not give enough information. He may want to know how long the tube may be used with 5 ma at the same or some other Kv P, or he may wonder how the rating is altered when a change is made in the operation of the tube from a constant voltage generator



Courtesy General Electric Corporation

FIG 71 A typical rating chart.

to one in which energy is utilized only in alternate half-cycles (see next chapter)

Modern practice gives the answer to such questions because the manufacturer supplies charts from which exposure times can be read off for corresponding voltage and current values, a separate chart being supplied for each type of supply equipment, such as full wave, half wave. (Again see next chapter.) Figure 71, taken from General Electric literature is an example of one of the

actual charts for the Coolidge Tube unit DX2-45. It applies when a  $20 \times 20$  mm focal spot is used and the tube is operated on full wave rectified equipment. To make sure that he understands the use of such a chart, the student should check the values given in Table XI. These are read off one of the graphs of Fig. 71.

TABLE XI

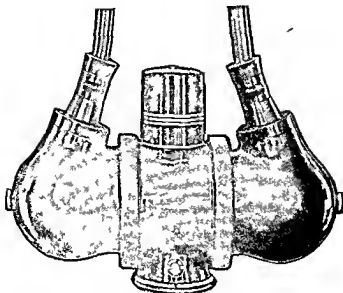
kV P	ma	Exposure Time
100	60	1/20 sec
86	60	1/5
70	60	1
54	60	5
40	60	20

It is important to note that, although the exposure time in the first line of this table is 400 times less than that in the last line, the power supplied the tube is only  $2\frac{1}{2}$  times greater. In other words, it is a bad mistake to assume that if it is permissible to expose for 1 second with a certain amount of power, that five times that amount could be used for a fifth of a second. Time must be allowed for heat developed to be removed, hence a greater and greater limitation is placed on the permissible power the shorter we make the exposure.

**68 Shockproof Tubes** — In section 64 reference was made to the necessity of protecting a tube so that x rays do not leave it in unwanted directions. Protection against electrical shock arising from contact with high tension wires is equally important. For a great many years both the electrical leads to a tube and its terminals were unprotected and there was always present very real danger of bad electrical shocks to patient and operator because of accidental contact with these conductors. Nowadays, although this danger is still often present, many tubes are *shockproof*, that is, they are so protected that it is perfectly safe to put one's hand on the casing in which the tube is housed.

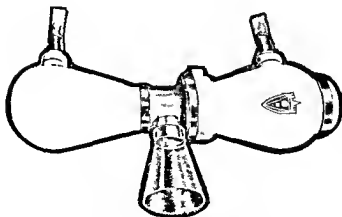
Figures 72 and 73 illustrate the general appearance of two such tubes. The means of providing protection is extremely simple. The tube proper is enclosed in a metal case which is grounded, and the high tension leads to the tube are surrounded by heavy insulating material around which a flexible grounded metallic casing is wrapped.

**69 Oil-immersion** — The design and general arrangement of the earthed casing of a shockproof tube must be such that there is no danger of



*Courtesy General Electric X-ray Corporation*

FIG. 72 A shockproof x ray tube



*Courtesy Philips Gloeilampenfabrieken X-ray Works*

FIG. 73 A shockproof x ray tube

breakdown sparking between any high tension part of the tube and the surrounding casing. In Fig 73, a Philips' tube, this is done by suitable design of the parts. In Fig 72, a General Electric tube, the space between the tube and the casing is filled with oil, the whole being hermetically sealed. Because of its insulating properties oil minimizes the space necessary between high tension and earthed parts. The use of oil also makes the arrangement independent of atmospheric conditions and, moreover, oil is superior to air as a heat absorbing and cooling medium."

In this connection it is interesting to note that the General Electric Corporation have units in which not only the x ray tube, but also the high voltage equipment, transformer and all, are enclosed in oil in a grounded container.

**70 Low Voltage Tubes** — A tube operated on voltages of the order of 50,000 volts has been designed largely because of the work of Chaoul, for the treatment of both malignant and nonmalignant skin diseases. The im-

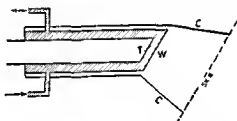


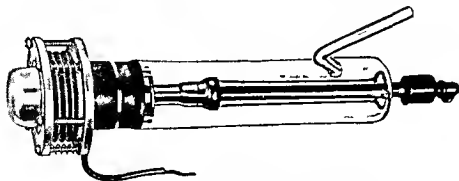
FIG 74 The target and treatment end of a Chaoul therapy tube

portant feature of the Chaoul tube is the anode end. The electrons, indicated by the dotted lines in Fig 74, pass down an earthed metal cylinder and strike at its far end a target *T*, made of gold plated nickel only 0.15 mm thick. Water circulating in a narrow region around the target end of the cylinder effectively cools the target. Because of the extremely small thickness of the target the x-rays generated pass through it with slight absorption, as well as through the 2 mm thickness of water between the target and the outer wall *W*. A conical applicator *CC* slipped over the end of the tube rests on the skin of a patient, the rays striking the skin at focal distances of only a few centimeters.

In Chapter X information will be given concerning the connection between the kind of rays leaving any type of tube and the applied voltage. In the Chaoul therapy tube the voltage is of the order of 10,000 volts.

**71 Low Voltage Tube Emitting Rays of High Intensity** — Michlett Laboratories, Inc., recently have put on the market an x ray tube

designed to produce x-ray beams of intensities thousands of times greater than any which have been described in this chapter. A brief reference will be made to one or two novel ideas utilized in this tube, a photograph of which

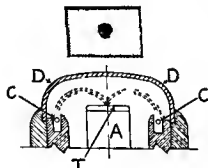


*Courtesy Machlett Laboratories Inc*

FIG 75 Photograph of a low voltage high power tube of new design

is reproduced in Fig 75. The dome at the extreme end of the tube, represented by *DD* in Fig 76, is an approximately hemispherical window made of the metal beryllium, a material which, as will be seen in Chapter X, absorbs x rays of long wave lengths to an extremely slight degree. The beryl-

luminum window is at ground potential and is in electrical contact with the cathode which is a heated filament, annular in shape, being represented by *CC* in Fig 76. The water cooled anode *A* is at a potential of some 60 kilovolts above ground, the face of the target *T* extending beyond the level of the cathode. Because of the electric field between the positive anode and the negative cathode (and window) the liberated electrons traverse a path somewhat as shown by the dotted lines in the figure, hitting the target at the focal spot. By varying the distance between the target and the window, the nature of the focal spot can be



*Courtesy Machlett Laboratories Inc*

FIG 76 *DD* represents the dome of the tube shown in Fig 75, *CC* the cathode, *A* the water-cooled anode, *T* the target. The black spot at the top is a pinhole photograph of the focal spot.

altered. The black spot at the top of Fig 76 is a pinhole photograph of the focal spot for one arrangement. Anticipating later work on dosage, we may mention in passing that, with a tube of this kind operated at 60 kilovolts and a current of 100 ma, the manufacturers estimate that intensities

of the order of 5 million roentgens per minute are obtained, over an area of 25 sq cm. By way of contrast, dosage values in Chaoul therapy are of the order of 100 roentgens per minute at a distance of some 5 cm from the target.

### PROBLEMS AND QUESTIONS

1. Compare the hot filament x-ray tube with the gas x ray tube with respect to (i) degree of vacuum, (ii) origin of electrons, (iii) control of current
2. What is the chief advantage of a line focus over a circular focal spot whose diameter is equal to the width of the line?
3. What methods are used to keep the target of an x-ray tube cool? Why is this desirable?
4. What are two special features of the metalix x-ray tube?
5. Describe very briefly three means which are utilized for keeping down the temperature of the target of a tube
6. Discuss the blackening of a gas tube with reference to its causes and the means of lessening it
7. Discuss the relation of the size of the focal spot to (i) the power which may be supplied to a tube, (ii) the character of the radiographs taken, (iii) the question of treatment
8. Why should a target of an x-ray tube be of high atomic weight?
9. When a hot filament tube is in good condition and 100,000 volts are applied across its terminals, the filament circuit not on, what should the milliamperage meter read? If in such a case a glow were observed in the bulb, what conclusion would you draw?
10. What is meant by saturation tube current?
11. What effect has increasing the voltage across a hot filament tube on the tube current? What effect in the case of a gas tube?
12. What connection is there between the focal spot and the input of an x ray bulb? Why may much larger x ray tube currents be used for a short time than for long periods?
13. Describe as fully as you can the essential features of a good modern x ray tube suitable for general diagnostic work
14. What are the special features of the Chaoul therapy tube?
15. What is the special advantage of the rotating anode tube?
16. Make a diagram to illustrate the principle of a stabilizer by means of which a hot filament tube current may be kept constant
17. A slight increase in the voltage applied to a Coolidge tube in general does not change the tube current, whereas a slight change in the filament current may cause a marked change in the tube current. Explain the reason
18. In a hot filament x ray tube, explain (i) two methods of obtaining the equivalent of small focal spots with adequate power input, (ii) two methods of keeping the target cool
19. Find the number of electrons which hit the target of a hot filament x-ray tube in 2 seconds, if the tube current is 20 ma
20. Name and explain two ways of utilizing an increased amount of power in an x ray tube without enlarging the effective size of the focal spot

## CHAPTER VII

### VALVE RECTIFICATION

**72 Self-rectifying Tubes** — We have already emphasized that electrons leave a hot filament only when it is negative. Hence, if a tube such as the Universal Coolidge is placed directly across the high tension terminals of a transformer, current ordinarily passes only when the end of the secondary of the transformer which is attached to the anode, is positive. In the next half cycle, when this end is negative, no current passes. Provided certain precautions are observed therefore, a tube can act as its own rectifier, and so be used with the simple arrangement shown in Fig 77. This is known as *self-rectification*. In Fig 78 graph (a) represents the theoretical wave-form of the voltage applied to the tube, and (b) shows the theoretical\* corresponding tube current. Note that it is intermittent but unidirectional.

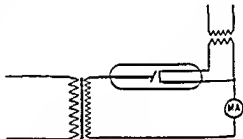


FIG 77 An x ray tube acting as its own rectifier

In actual practice, in the great majority of cases, it does not do to let a tube act as its own rectifier. As we have already pointed out more than once, the focal spot on the target may become very hot. In the Universal tube, the whole anode sometimes becomes white hot. Now any metal emits thermionic electrons at high temperatures, hence, if an alternating high tension potential is applied to the tube, there is always the danger that, during the half-cycle when the anode is negative, it will emit electrons due to a high temperature. Such an emission is disastrous to the tube. In addition to causing the liberation of unwanted x-rays from places where these electrons strike, this beam from a hot anode may destroy the tube by the damage it does on impact. More often than not, therefore, hot filament tubes are operated

\* By means of oscillographs the actual form of the curve can be obtained. Although it departs somewhat from the smooth type of curve shown in Fig 78, the form of the current graph obtained by the oscillograph shows clearly the suppression of each half cycle.



on voltage which has been rectified, and invariably the rectifiers used are of the valve type, not the mechanical rotating disc described in section 19

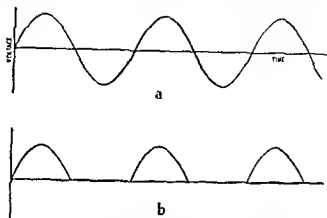


FIG 78 In self rectification, or half wave tube current flows only in alternate half-cycles

**73 Valve Rectifiers** — As long ago as 1915 Dr Saul Dushman, of the General Electric Research Laboratory, designed a rectifying valve for use in x-ray circuits, to which the name *kenotron* was given. The simple arrangement utilizing a rectifying valve is shown in Fig 79, where a single valve  $V$  is in series with the secondary of the high tension transformer and the tube  $T$ . It is well to note that, in order to avoid confusion, in all our diagrams we represent a valve by a circular diagram and an x ray tube by a cylindrical one. Actually they may both be cylindrical in shape.

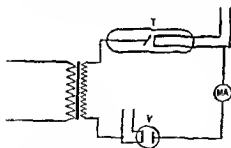


FIG 79 Half wave rectification by means of a single valve  $V$  in series with the tube  $T$

Although in one sense a rectifying valve and a hot filament x-ray tube are essentially the same, each with an anode and a hot filament cathode

and each permitting the flow of electrons only when the filament is hot and when it is negative, nevertheless there are important differences. A tube is primarily for the production of x rays, whereas in a good valve, x-rays must not be generated. To avoid their production, the electrons must not be allowed to cross the valve at high speed, or, in other words, the voltage drop across the

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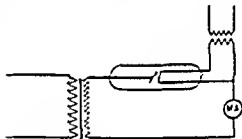


FIG. 77 An x-ray tube acting as its own rectifier

in Fig. 77. This is known as *self-rectification*. In Fig. 78 graph (a) represents the theoretical wave-form of the voltage applied to the tube, and (b) shows the theoretical\* corresponding tube current. Note that it is intermittent but unidirectional.

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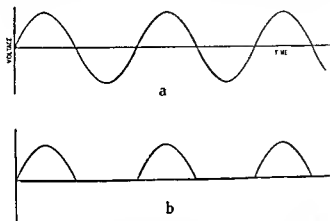


FIG 78 In self rectification, or half wave, tube current flows only in alternate half-cycles

**73. Valve Rectifiers.** — As long ago as 1915 Dr Saul Dushman, of the General Electric Research Laboratory, designed a rectifying valve for use in x-ray circuits, to which the name *kenotron* was given. The simple arrangement utilizing a rectifying valve is shown in Fig 79, where a single valve *V* is in series with the secondary of the high tension transformer and the tube *T*. It is well to note that, in order to avoid confusion, in all our diagrams we represent a valve by a circular diagram and an x ray tube by a cylindrical one. Actually they may both be cylindrical in shape.

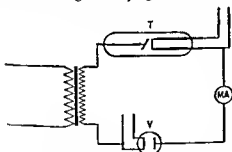


FIG 79. Half wave rectification by means of a single valve *V* in series with the tube *T*

Although in one sense a rectifying valve and a hot filament x-ray tube are essentially the same, each with an anode and a hot filament cathode and each permitting the flow of electrons only when the filament is hot and when it is negative, nevertheless there are important differences. A tube is primarily for the production of x-rays, whereas in a good valve, x rays must not be generated. To avoid their production, the electrons must not be allowed to cross the valve at high speed, or, in other words, the voltage drop across the

valve must be small. This is also desirable, because the greater the voltage drop across a valve placed as in Fig. 79, the less the voltage available for the tube.

In a good valve then, the aim is to pass a high current at a low voltage. To insure this the valve must be so designed that the current through it is considerably below the saturation value. In section 62, the meaning of saturation current for an x-ray tube was explained, use being made of the graphs of Fig. 55. Because of the fundamental similarity between a tube and a (vacuum) valve, the same type of graphs apply to a valve. In fact,

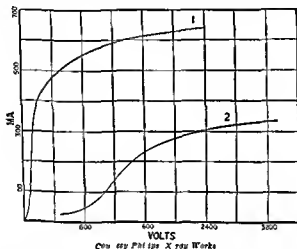


FIG. 80 Characteristic curves for two rectifying valves. 1 metal x 2 glass

Fig. 80 taken from literature of the Philips' Metal x Company, shows two similar graphs for two different types of rectifying valves. A glance at graph 1 will show that the valve to which this applies will pass a current of 300 ma when the voltage across it is less than 200 volts, a very small amount compared with tube voltages.

**74 Types of Valves** — The original kenotron and the kind of valve first put on the market by the Philips' X-ray Works were simple diode tubes, consisting essentially of the filament (and associated cathode) and the anode, in a highly exhausted glass container. In some respects this arrangement proved unsatisfactory because with an unprotected filament, a negative charge collects on the inner surface of the glass walls and this makes the valve erratic in its behavior. To quote from General Electric literature "this charge (the charging of the walls) produces a grid action which under variable circuit

conditions may produce a voltage drop as high as 10,000 to 20,000 volts "

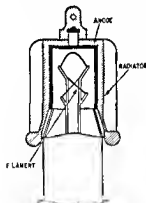
To overcome this defect, different devices have been used For example the General Electric now use "a cylindrical anode with a spiral filament inside." Since the filament is thus surrounded, no negative charge accumulates on the glass container as all the electrons are caught by the anode Figure 81 is a photograph of a kenotron of this type



*Courtesy General Electric X-ray Corporation*

FIG 81 A kenotron (rectifying valve) with cylindrical anode surrounding a spiral filament

The Philips' Metalix Company have overcome the difficulty by making one end of the valve a metal cylindrical cap, which fulfills the double function of forming part of the container and acting as the anode This anode "incloses the filament in all directions except in that of the insulating stem which supports the filament" The general arrangement is shown in Fig 82 In Fig 80, curve 1 applies to a metalix valve of this sort, curve 2 to one with a glass envelope, the filament current in each case being the same The marked superiority of the metalix valve is obvious



*Courtesy Philips X-ray Works*

FIG 82 Diagram of a rectifying valve with metal anode surrounding the filament

Figure 83 shows the external appearance of a valve of a different kind, recently put on the market by the Philips' Company. In this type residual gas is left in the valve and use is made of cumulative ionization by collision Just as in the high vacuum type, electrons are emitted from the filament (of the dull emitter type) when it is negative, but the current is no longer a pure electron stream, for the gas is ionized by the colliding electrons On the reverse half-cycle, when the filament is positive there is no electron emission and

no ionization In this type the manufacturer states that "the voltage drop across it remains constant at a figure of the order of 50 volts" and that "hollow intermediate conductors, situated at intervals along the interior of the discharge tube are interconnected by condensers which encircle the unit and perform the function of distributing the potential by equal stages along

the length of the valve." Currents as high as 1000 ma. are possible with this kind of valve.

**75. Half-wave Rectification.** — Attention has already been directed to Fig. 77, the simple self-rectified circuit, and to Fig. 79, where a single rectifying valve in series with the tube gives rectification and added protection. To each of these circuits Fig 78 is applicable. With the arrangement shown



Courtesy Philips X-ray Works

FIG 83 A rectifying valve which will carry currents as high as 1000 ma

in Fig 79, however, it is possible to use greater amounts of power than if the tube were its own rectifier. This figure illustrates the simplest case of *half-wave rectification*

**76. Full-wave Rectification.** — Figures 84a and 84b illustrate a type of rectified circuit in common use, the so-called Graetz circuit. In Fig. 84a

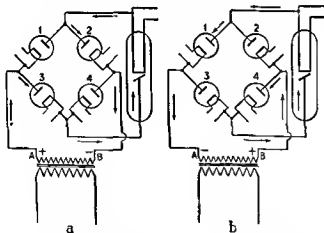


FIG 84 The Graetz circuit for full wave rectification.

the arrows indicate the direction of the current during the half-cycle when the end *A* of the secondary of the high-tension transformer is positive, and the end *B* negative. Figure 84b applies to the alternate half-cycles when *A* is

negative and *B* positive. If the student will remember that current will traverse a valve only when the filament is negative, he should have no difficulty in showing that in Fig. 84*a*, valves 1 and 4 are not in use, or in Fig. 84*b*, valves 2 and 3, but that in each case current passes through the x-ray tube. With this arrangement, therefore, use is made of each half-cycle, the theoretical form of the current being as shown in Fig. 85.

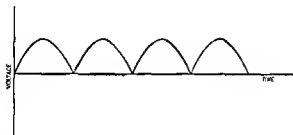


FIG. 85 In full wave rectification there is tube current every half cycle

**77 Tube Rating and Type of Rectification** — In Fig. 71 an example of a rating chart for a certain tube was given. Now, as a matter of fact, the graphs in this chart were only applicable when this tube was operated on full-wave equipment, and, in the manufacturer's literature, two other charts were given for the same tube, one applicable to half wave, the other to self rectified equipment. In explaining why a different chart is needed for each type of equipment, it is instructive to look at a concrete case.

From the three charts supplied by the General Electric Company for their RB 1-4 tubes (with small focal spot) one finds out that, when one of these tubes is operated on 60,000 volts, with 20 ma. current, the maximum permissible exposure time is 40 seconds for full-wave equipment, 15 seconds for half-wave, and 2 seconds for self rectification. It is not difficult to see why with self-rectified use the same amount of power can be used for a much shorter time than with half-wave rectification. Without the valve, there is danger of inverse current through the tube, once the focal spot reaches a certain temperature. The presence of the valve, however, does not allow any current to flow even when the focal spot reaches this or a higher temperature.

It is not so easy to see why the permissible time for operation on full wave is longer than on half-wave. To understand the reason the student must be clear about the difference between the current recorded by the milliammeter in the tube circuit, and the actual value it may attain in a half cycle. Consider half-wave rectification, where the current is completely suppressed every alternate half-cycle, and where an oscillograph shows the intermittent, pulsating

nature of the current, somewhat as in Fig 86, curve *a*. The current changes, however, are much too rapid (remember that the time of a half cycle is  $1/120$  second for a 60 cycle per second supply) to be registered by the moving parts of a milliammeter, and this instrument records only a steady mean, of magnitude considerably less than the highest values reached every alternate cycle. In Fig 86, the line *b* represents the steady mean current recorded by the milliammeter. It follows that, if a milliammeter records, say 20 ma, the

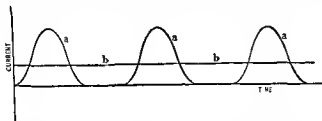


FIG 86 The line *b* represents the steady current recorded by a milliammeter in half wave rectification

current through the valve and the x-ray tube may actually attain a value several times 20 ma — at least three times as great, according to information taken from Philips' literature

Now consider full-wave rectification, as depicted in Fig 87. In this case, because current passes through the tube *every* half-cycle the mean milliamperage is much nearer the peak value, this being only one and a half

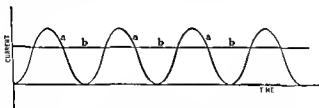


FIG 87 The line *b* represents the steady current recorded by a milliammeter in full wave rectification

times as great as the mean. Thus for a milliammeter reading of 20 ma, the actual tube and valve current may be as high as 60 ma for half-wave rectification, and about 30 ma for full-wave. Hence, although the total power supplied a tube in each case may be the same (an average of 20 ma at a peak voltage of 60,000), in the case of half-wave equipment, it is given in "doses" which are much more intense, but half as frequent as in the case of full-wave. Since heat generated at the focal spot takes an appreciable time to be dissipated, this means that higher focal temperatures are reached



with half wave than with full-wave, with consequent shorter permissible times of tube operation

**78 The Use of Condensers with Valves.**—Consider a circuit arranged as in Fig 88, where *C* represents a condenser of fairly high capacity and one capable of withstanding x-ray potentials. During the half-cycle when *A* is positive and *B* negative, as in Fig 88*a*, current can flow both through the x-ray tube and into the condenser, charging it as indicated in the diagram, the potential difference across the condenser being the same as across the tube. During the next half-cycle, as represented in Fig 88*b*, no current can flow

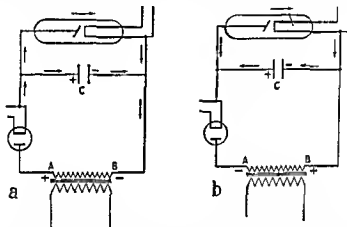


FIG. 88 To illustrate the use of a condenser for applying an approximately constant potential across an x-ray tube

from the transformer because the negative end of its secondary is attached to the anode side of the rectifying valve. During this half cycle, however, the condenser can discharge through the tube, with a drop in voltage which is small compared with the maximum potential to which it was charged. To understand why the voltage drop is small, let us make an estimate using actual numerical values.

Suppose the average tube current during this discharge of the condenser is 20 ma. and that the capacity of the condenser is 0.1 microfarad. Then during a half cycle of  $1/120$  of a second, the quantity of electricity which leaves the condenser

$$\begin{aligned}
 &= \frac{20}{1000} \times \frac{1}{120} \text{ ampere seconds or coulombs} \\
 &= \frac{1}{6000} \text{ coulomb}
 \end{aligned}$$

But, since the capacity of the condenser is  $\frac{1}{10}$  mf or  $\frac{1}{10} \times 10^{-6}$  farad, if  $V$  is the voltage drop, the quantity of electricity which leaves the condenser also

$$= \frac{1}{10} \times 10^{-6} \times V \text{ coulomb.}$$

$$\therefore 10^{-7}V = \frac{1}{6000}$$

or

$$V = 1667 \text{ volts}$$

Compared with the peak voltage developed in the secondary of the transformer, this is slight

With the above arrangement, then, the voltage applied to the tube will remain moderately steady, somewhat as represented in Fig 89, a copy of a diagram published by Watson and Sons (Electro-medical) Limited, London.

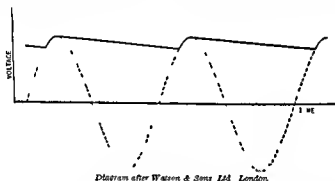


FIG 89 With the arrangement shown in Fig 88, the drop in tube voltage is slight

**79 The Greinacher Circuit** — In the above arrangement we have noted that during every alternate half-cycle the transformer does not supply any power to the circuit. Actually condensers and valves are used in less simple arrangements. The Greinacher circuit shown in Fig 90 is an example of one arrangement which has been widely used. In it, by the use of two condensers and two valves, (1) the transformer is utilized every half-cycle, (2) the voltage drop across the tube is slight, and (3) approximately twice the transformer voltage is applied to the tube.

By reference to Fig 90, it will be seen that, during the half-cycle when  $A$  is positive and  $B$  negative, condenser  $C_1$  is charged to the maximum voltage developed in the secondary of the transformer, whereas on the alternate half-cycle, when  $A$  is negative and  $B$  positive,  $C_2$  is similarly charged. Once the

condensers are charged, *each* of them can send a current through the x-ray tube, since in the circuit 1 2 4 3 the condensers and the tube are in series. Moreover, just as explained in the previous section, the voltage drop in each half-cycle will be slight. Again, since each condenser is charged to the transformer voltage and the two are in series with the tube, the tube voltage is approximately twice that of the transformer.

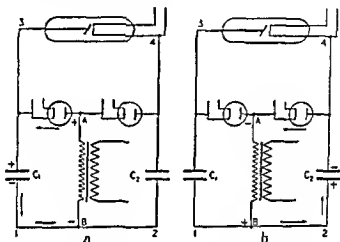


FIG. 90. The Greinacher constant potential circuit

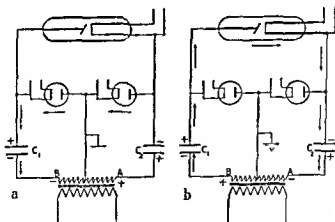


FIG. 91. The Villard circuit by means of which an intermittent potential twice that developed in the transformer is applied to the x ray tube

**80 The Villard Circuit** — This circuit, also widely used, is illustrated by Figs 91 and 92. By means of it double the transformer voltage is applied to the tube, but the tube current is not continuous as in the Greinacher arrangement. As will be seen by a study of Fig 91a, during the half-cycle when *A* is positive and *B* negative, current can pass through the valves, the condensers consequently being charged as indicated. On the reverse half-cycle as shown in Fig 91b, current cannot pass through the valves, but each condenser can discharge through the tube, while at the same time, the voltage developed in the secondary of the transformer is also in the right direction to cause a tube current. Since the two condensers, the secondary of the transformer, and the tube are all in series, as can be seen in Fig 91b or Fig 92, the resultant

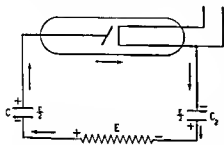


FIG 92 A portion of the Villard circuit illustrating the half cycle in which both condensers and secondary of transformer cause a tube current

voltage causing a tube current is equal to the sum of the transformer voltage plus that across  $C_1$  plus that across  $C_2$ .

Now, in a simple circuit such as shown in Fig 93, where two condensers of equal capacity are joined in series with a battery, the voltage drop across each condenser is just one half the E M F of the battery. In Fig 91a when the current is passing through the two valves with the condensers in series, we have essentially the same circuit the secondary of the transformer replacing the battery. The condensers, therefore, are each charged to a voltage of  $V/2$ , where  $V$  is the effective voltage developed by the transformer. Hence, in Fig 91b the effective voltage applied to the tube is  $V + V/2 + V/2$  or  $2V$ . Figure 94, taken from valve literature by the Philips' Metalix Company, is an actual oscillographic record showing the changes in tube current in a Villard circuit.

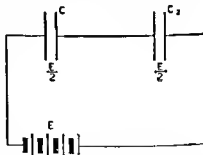


FIG 93 When two condensers are in series with a battery of E M F volts, the potential difference across each condenser is  $E/2$  volts

It will be noted that two valves are used in the above arrangement. Actually this is not necessary and in the original circuit, only one was used. It was

found, however, that by using two valves, with grounding and the balanced arrangement of Fig 91, more satisfactory operation was obtained, and, moreover, the circuit was more suitable for use with shockproof tubes.

We have by no means exhausted the types of rectifying circuits, but, as the aim of this book is to explain principles rather than give exhaustive tech-



*Courtesy Philips Meiditz*

FIG 91 An actual oscillogram of tube current when ordinary metalix tube is operated by Villard circuit

nical details, it is considered that enough has been given to make clear the fundamental ideas. So far, too, we have confined our attention to arrangements and devices used for ordinary diagnostic and moderate voltage therapy circuits. We have still to discuss ultra high voltage arrangements, but, before doing so, it is advisable to consider in detail the properties and nature of x-rays themselves.

## PROBLEMS AND QUESTIONS

1 Make a fully labeled diagram of the electrical connections in an x ray tube outfit which utilizes the following features (i) autotransformer control; (ii) a four valve rectifying arrangement (the Graetz circuit); (iii) a hot filament x ray tube; (iv) a filament current ammeter (for x ray tube), and (v) a milliammeter in tube circuit. Indicate by arrows the current path in the tube circuit during one half cycle.

2 Explain, with the aid of simple diagrams, the difference between self rectification, half wave rectification, and full wave rectification.

3 Why is a rectifier desirable in operating a standard universal Coolidge tube but not necessary for the radiator Coolidge tube?

4 Under what circumstances can a very high vacuum be made conducting? Describe the mode of conduction.

5 Explain by means of a simple diagram, the use of (i) a mechanical rectifier for high tension voltages (ii) a single valve hot filament rectifier. What is the difference in the nature of the tube currents for the two cases?

6 With the aid of diagrams describe and explain a rectifying circuit for an alternating high tension voltage, (i) using every half cycle, by means of a single valve and a condenser; and (ii) using alternate half cycles, but (approximately) doubling the transformer voltage.

7. A hot filament tube, whose filament is heated by a step-down transformer, is operated by a high tension transformer, with autotransformer control, and with a Villard rectifying arrangement. Make a complete diagram of the electrical system.

8. A condenser of a capacitance  $1/10$  microfarad is charged to 200,000 volts. It then maintains an average current of 10 ma through an x-ray tube for  $1/100$  second. Find the voltage across the condenser at the end of this time. *Ans.* 199,000 volts.

9. With the aid of two diagrams, one for each half-cycle, show how a condenser may be combined with a single rectifying valve and transformer to maintain an approximately steady voltage across an x-ray tube.

10. Make a diagram showing the essential connections when an x-ray tube is operated by a transformer rectified by a Greinacher circuit.

11. A hot filament x-ray tube is operated with a full-wave rectifying arrangement. The P.D. across the primary of the high tension transformer is controlled by a rheostat and all hot filaments are heated by step-down transformers. Make a careful diagram showing all essential circuits.

12. Make a diagram of the circuit you would use to obtain the characteristic curve (that is, tube current against voltage) for a diode valve or a rectifying valve. Indicate the nature of the curve you would obtain.

13. Make a complete diagram showing the essentials of an x-ray high tension circuit with autotransformer control of voltage and a *full-wave* rectifying circuit.

14. Make a labeled diagram showing the essential connections, when a hot filament x-ray tube is operated, with autotransformer control of voltage and the Greinacher constant potential circuit. Show complete filament and primary circuits.

## CHAPTER VIII

### HIGH FREQUENCY CURRENTS AND ELECTRIC WAVES

**81. Classification of Currents** — In this chapter a short account is given of the means of generating rapidly oscillating currents, a subject which is of importance because of the therapeutic use of such currents and also because they are fundamental in the generation of electrical waves. X-rays, as will be seen later, are a special kind of electric waves. At the outset we summarize the various types of currents with which a student of radiology should be familiar. There is first of all the broad classification, used by the practical electrician, into D C and A C, that is, into unidirectional and alternating currents. Under D C we include the following:

(1) The steady current which is maintained in a simple circuit by a constant source of E M F such as a storage battery, or a D C dynamo, or any good cell. Such a current at one time was designated *galvanic*, the term *galvanism* being applied to the use of such currents.

(2) *Intermittent unidirectional current*, such as that through a self-rectified x-ray tube, or a tube operated by a transformer with mechanical rectifier.

(3) *Pulsating direct* — This kind is somewhat similar to an intermittent current, except that in pulsating the current need not necessarily drop to zero between pulses of maximum intensity. A pulsating current can be obtained by the use of a mechanical device whereby resistance is regularly taken out of a circuit or added to it.

(4) *Primary faradic* — This is the name sometimes given to the current in the primary of an induction coil controlled by a hammer break. This also is an intermittent current, but one which is characterized by the abruptness with which the current drops to zero value. (See Fig. 14.) Due to this abruptness, a marked stimulus may be applied to a muscle or a nerve by the use of such a current.

(5) *Secondary faradic* — Currents through the secondary of an induction coil can be classified as direct, if the magnitude of the induced E M F on make is so small that no appreciable inverse current flows. In a good coil this should be the case. Frequently, however, inverse current is present, and, if so, secondary faradic should more properly be classified under A C.

7 A hot filament tube, whose filament is heated by a step down transformer, is operated by a high tension transformer, with autotransformer control, and with a Villard rectifying arrangement. Make a complete diagram of the electrical system.

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The following can properly be classified as A C

(1) The gradually changing *sinusoidal* current represented by the smooth curve of Fig 4 Commercial A C of 25 or 60 cycle per second approximates to this kind

(2) High Frequency The term *high* is applied when the frequency of alternating currents reaches a value of the order of 100,000 cycles per second. Frequencies of a million and more cycles per second are quite common, and it is now not unusual to use values as high as 300 million or even higher. When such currents pass through tissue, there is not the marked stimulus resulting in muscular contraction or painful sensation which faradic or even low frequency currents cause. High frequency currents, however, have the important applications noted below

**82 The Generation of Damped H F Currents** — H F currents may be divided into two classes according as the oscillations are damped or undamped. First we consider the generation of damped currents

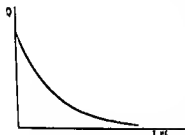


FIG 95 Graph representing the aperiodic discharge of a condenser

When a condenser is charged, and then discharged, the discharge current is one of two kinds. If the terminals of the condenser are connected by a fairly high resistance, a steady direct but gradually decreasing current flows until the condenser is completely discharged. This type of discharge, the *aperiodic*, is represented by the graph in Fig 95. If the resistance is low, an oscillatory discharge, as represented by Fig 96, takes place. The reversals of current mean that

the condenser is discharged, recharged in the opposite sense, discharged again, and so on, the process continuing until the energy originally stored is ultimately dissipated in heat, and, sometimes, in radiation. In an ideal arrangement with negligible resistance, no heat would be developed, and the oscillations would continue for a long time — not indefinitely, however, because, as we shall see later, radiation of electromagnetic waves takes place when the oscillations are sufficiently rapid.

An almost exactly analogous phenomenon takes place with an oscillating simple pendulum. If the "bob" of the pendulum is drawn to one side and then released, oscillations are executed until the original potential energy communicated to the system has all been dissipated in heat as a result of mechanical friction between the moving bob and the air. During the time that the oscillations are taking place, a constant exchange is going on between the potential

energy (P E) of the displaced bob and its kinetic energy (K E). At the end of each half oscillation, the P E is a maximum and the K E zero, whereas at the middle position, the opposite is true. Because of the small air resistance, this interchange goes on for some time before finally all the original P E is converted to heat.

Mathematical treatment of the oscillations in both the mechanical system and the electrical shows that the analogy may be pushed still further. Resistance is akin to friction and current to the velocity of the pendulum bob. When the bob is in its lowest position where its velocity is a maximum, its inertia causes it to "overshoot the mark" and to store up P E on the other side. So, too, when a condenser has been momentarily emptied, because of inductance, the current continues to flow and so the condenser is charged in the opposite sense. It will be recalled (see section 6) that, whenever a current in a circuit is changing, an induced E M F or an E M F of inductance is present which opposes the change. Moreover, the greater the inductance of the circuit, the greater the magnitude of this opposing E M F. Hence we may consider inertia and inductance as analogous quantities. In a mechanical system, the greater the inertia of a body the greater its tendency to keep on moving when in motion, in an electrical circuit the greater the inductance, the greater the tendency of a current to persist once it is started.

When these facts are put in mathematical language, exactly similar equations are set up for the mechanical and the electrical systems. From such equations

it is not difficult to show that, if  $R < \sqrt{\frac{4L}{C}}$ , where  $R$  is the resistance in ohms,

$L$  is the inductance in henries, and  $C$  is the capacity in farads, an oscillating discharge takes place, and that, for low values of  $R$ , the frequency of the oscillations is given by

$$f = \frac{1}{2\pi\sqrt{CL}}$$

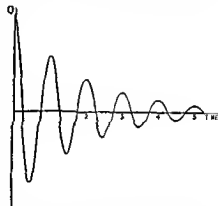


FIG 96 Graph representing the damped oscillatory discharge of a condenser

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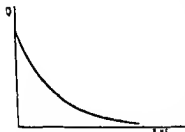


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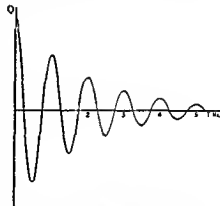


FIG. 96 Graph representing the damped oscillatory discharge of a condenser

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$$f = \frac{1}{2\pi\sqrt{CL}}$$

For example, if  $C = 0.002$  microfarad, and  $L = 1.27 \times 10^{-3}$  henry,  $f$  comes out to be nearly one million cycles per second.

It will be noted that, the greater the value of  $L$  and the greater  $C$ , the smaller the value of  $f$  or the lower the frequency. As far as  $L$  is concerned this is just what we should expect, because, as we have noted above, the greater the inductance, the greater the force resisting changes, or the more "sluggish" the current is. As far as  $C$  is concerned, it is not difficult to understand why an increase in  $C$  should slow down the oscillations. Since at any instant, the voltage across the condenser  $= Q/C$ , it follows that the larger  $C$  the longer the time it takes for this potential difference to reach its maximum value during a half cycle. For very rapid oscillations, then, both  $C$  and  $L$  should be small.

**83 Experimental Demonstration of High Frequency** — Suppose a Leyden jar of capacity  $C$  is joined to the terminals  $A, B$  of a Wimshurst machine, somewhat as shown in Fig. 97. When the machine is operated,

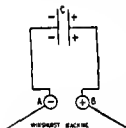


FIG. 97 The condenser  $C$  is charged by being connected with the terminals  $A$  and  $B$  of a Wimshurst machine.

a charge piles up on each of the condenser plates until a potential difference ( $Q/C$ ) develops which is sufficiently high to cause a spark to jump the gap  $AB$ . Because of the intense ionization associated with the spark, the gap becomes temporarily a region of low resistance, and an oscillating discharge of the condenser takes place. If this spark is examined in a revolving mirror, it is seen as a succession of flashes, not a single spark. By using an oscillograph, it may be shown in a still better way that the current when the condenser is discharging is oscillatory. Actually the oscillograph record shows a curve similar to that of Fig. 96.

If fairly high values of  $L$  and of  $C$  are used, it is possible to take readings in the laboratory from which a plot of the oscillatory discharge may be made, provided some means, such as the *Webster Drop Chronometer*, is available for measuring very small time intervals. With such a device, it is possible after charging a condenser, to measure with a ballistic galvanometer, the charge left in it after each of a series of short but gradually increasing time intervals during which the condenser is allowed to discharge. The writer has recently examined the laboratory report of a group of students who had obtained in this way an excellent oscillatory curve using  $C = 1$  microfarad and  $L = 0.76$  henry.

**84 Primary Tesla Circuit** — When a single complete discharge takes place with an arrangement like that of Fig. 97, the oscillations are heavily damped even with small resistance, and the total number of cycles is small. To make practical use of high frequency currents, a succession of discharges must be available. This is readily accomplished by any arrangement which recharges the condenser nearly as fast as it is discharged. A common arrangement is shown in Fig. 98, where *P* and *S* represent the primary and secondary of a step-up transformer, *A* and *B* are the terminals of a spark gap, *C* is a condenser and *L* an inductance. A few turns of heavy copper wire make a convenient inductance for many experiments. Since the plates of the condenser are always in electrical contact with the terminals of the secondary of the transformer, the condenser is repeatedly recharged after each complete

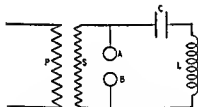


FIG. 98 The primary Tesla circuit, an arrangement for obtaining a succession of damped high frequency oscillations

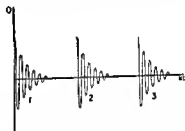


FIG. 99 The kind of high frequency currents obtained with the arrangement shown in Fig. 98

discharge in the oscillatory circuit *BACL*, and a succession of oscillation pulses is obtained. Figure 99 shows the nature of current in the oscillatory circuit with such an arrangement.

To the ear it seems as if continuous sparking were taking place, but actually the off-period, that is, the interval, between the pulses 1 and 2, 2 and 3, Fig. 99, may be many times longer than the actual time oscillations are taking place during a single pulse. For example, a small transformer, operated on 60 cycles per second, might recharge the condenser every half-cycle, that is, every  $1/120$  of a second. If, then, the frequency of the oscillations in the circuit *BACL* were a million per second, and there were 10 in a single pulse, the total time of a pulse or a complete discharge would be  $\frac{10}{1,000,000}$  or

$\frac{1}{100,000}$  of a second, a time many times shorter than  $1/120$  of a second, the interval between pulses.

Using such a circuit, one can show some striking experiments which demonstrate indirectly the existence of high frequency currents in the coil  $L$ . For example, if a tube containing the gas neon at low pressure is brought near this coil, or indeed, placed near almost any part of the oscillating circuit, the bright red luminous discharge characteristic of neon takes place in the tube. If one uses a carefully evacuated bulb into which a few drops of mercury have been distilled and the coil  $L$  consists of three or four turns of heavy copper wire wrapped around the center of this bulb, a brilliant discharge in the form of a ring occurs if the bulb is warmed to a suitable temperature.

A striking contrast to the mercury discharge is provided by using a bulb into which a little iodine has been distilled. If the vapor pressure of the iodine is regulated by having attached to the bulb a side tube immersed in ice and water, one obtains a brilliant greenish-pink ring discharge when the gap  $AB$  is a few millimeters wide, and a less bright yellow ring for a much shorter gap.

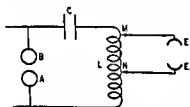


FIG. 100 An arrangement sometimes used in one type of diathermy

These luminous discharges provide evidence of the rapid high frequency currents in the coil  $L$ . Rapidly changing currents mean equally rapidly changing magnetic fields in the neighborhood of the coil. But, whenever a magnetic field is changing, there is an induced E M F whose magnitude is greater, the greater the rate of change of the field. Hence, in the region near the coil, or within a gas or a vapor contained in a tube placed within the coil, there exists an induced E M F. sufficiently great to cause a current in the gas, a current which is made evident by the luminosity.

**85 Diathermy with Damped Oscillations** — In medicine one of the commonest uses of high frequency currents is to develop heat in tissue, as is done in *diathermy*.

In one simple arrangement, electrodes  $E$  and  $E$ , Fig. 100, are attached by means of conductors to points  $M$  and  $N$  in the coil carrying the currents. The electrodes are made of pliable metallic material which are frequently enclosed in a rubber casing. In use, the electrodes fit tightly against a protecting layer of woollen material in contact with the skin of the patient. With such an arrangement heat is developed in the tissue which provides the conducting path between the electrodes, a sensation of warmth being all that is felt by the patient. By making one of the electrodes of small area, it is possible to concentrate the heat locally.

In diathermy with damped oscillations, the intensity of the treatment can



be controlled by altering the length of the spark gap. The shorter the gap, the smaller  $V$  the potential difference between the condenser plates, when a spark takes place. Since  $Q$ , the charge stored in the condenser, is equal to  $CV$ , it follows that the quantity of electricity taking part in discharge and hence the average value of the current, is less, the smaller the gap.

Sometimes instead of attaching electrodes directly to two points on the oscillating circuit, a secondary circuit is *coupled* with the primary oscillating circuit, somewhat as shown in Fig 101. Due to the coupling of the coils  $L$  and  $L_1$ , currents are induced in the circuit  $L_1C_1EE$ , the frequency of the induced electromotive force being the same as that of the oscillations in the primary. The intensity of the currents induced in the secondary circuit depends to a marked degree on whether or not the circuit  $L_1C_1EE$  is *tuned* or in *resonance* with the primary circuit. The student will recall that when regular periodic impulses are applied to a system capable of oscillating, the oscillations set up are of very high amplitude if the period of the impulses is the same as the natural period of the oscillating system. When this is the case, the system is vibrating or oscillating in resonance with the external periodic impulses. The oscillating currents induced in the circuit  $L_1C_1EE$  have their greatest intensity, then, when the natural period of this circuit is the same as that of the primary circuit. Since this natural period depends on the capacity (and the inductance), tuning to resonance is conveniently accomplished by making  $C_1$  a variable condenser. To measure the intensity of the high frequency currents, as well as to indicate when resonance has been obtained, an ammeter  $A$  may be placed in the circuit.

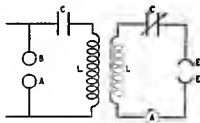


FIG 101 A diathermy arrangement which uses a secondary circuit coupled with the primary Tesla

**86 Secondary Tesla Circuit** — The arrangement shown in Fig 98 is sometimes called the primary Tesla circuit in honor of Tesla, one of the pioneer workers with high frequency currents. When high voltage as well as high frequency is wanted, a secondary Tesla circuit is added. A common arrangement consists in coupling with the primary coil  $L$  a solenoidal coil  $L_1$  of many turns of fine wire, as in Fig 102. If one end of  $L_1$  is grounded, sparks several centimeters long will jump from the other end to a grounded conductor. Because of the high frequency of the currents one may safely allow the sparks to jump to one's hand, or better, to a piece of metal held

tightly in the hand \* In the equipment frequently used,  $L$  is a ring or short solenoid of a few turns of heavy wire, and  $L_1$  is placed inside  $L$ .

In fulguration, by attaching a flexible conductor to the secondary coil, such sparks may be directed and used in localized treatment

**87 The Triode Vacuum Tube** — In order to give even the simplest explanation of how undamped high frequency currents are obtained, it is necessary to amplify somewhat the work previously given regarding the passage of electrons from a hot filament across an evacuated tube The student is asked to recall the graphs given in Fig 55 and Fig 80, which show the way in which the current across a hot filament x-ray tube or rectifying vacuum tube varies with the applied voltage, at constant filament

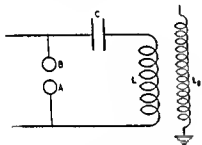


FIG 102 High frequency currents of high potential are developed in the secondary coil  $L_1$  if it is made of many turns

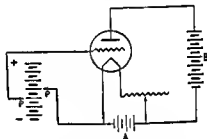


FIG 103 Circuit for examining the effect of grid potential on the plate current in a triode vacuum tube

temperature This type of curve applies to any *diode* vacuum tube, that is, a highly exhausted tube with filament and anode

In the *triode* vacuum tube, in addition to the filament which liberates electrons when heated, and the plate or anode, a *grid* constitutes a third element In the tube diagrams appearing in Figs 103, 105 and 106, the grid is represented by the central wavy line, but actually it is a spiral of fine wire, or a wire mesh, in close proximity to the filament The anode or plate more or less surrounds the grid To demonstrate the function of the grid, a circuit such as that illustrated in Fig 103 may be used With this arrangement by varying the position of the contact  $P$ , the potential of the grid with respect to  $P_1$  and hence with respect to the filament can be made either positive or negative It is possible then to maintain the plate at a constant potential

\* It is not wise to do this when using the undamped high frequency currents described in section 88

(by means of the battery *B*) and to examine the variation of the current to the plate when the grid potential is given a series of values, both positive and negative. The graph of Fig 104 shows the general nature of the result obtained when such an experiment is carried out. Note the following:

(1) For negative potentials greater than *OA*, there is no plate current. The actual value of *OA* is considerably less than the plate potential. For example, in a tube examined in a laboratory class by a student, for a plate potential of +70 volts, *OA* was -22 volts.

(2) The main portion of the curve is almost linear, in some tubes exactly so, in others somewhat curved. This is the important part of the curve, because normally the potential of the grid, or its *bias*, is such that the tube is operated on this portion of the curve.

(3) Saturation can be obtained, as in the diode, but it requires a fairly high positive grid voltage, and in using a triode as an oscillator (or a detector) it must be avoided. In making characteristic curves similar to that of Fig 104, it is really not necessary to extend the graph to this stage.

(4) By using a series of different plate voltages, a corresponding series of characteristic curves can be obtained. From an examination of these curves, the very important fact emerges that a small change in grid potential may bring about the same change in plate current as a much larger change in plate voltage. For example, in the case of the tube mentioned in (1) above, the student found that, with constant grid potential, a change of 30 volts in plate potential caused a change of 21 ma in the plate current, but, at constant plate potential, a change of only 8.25 volts on the grid brought about the same change in plate current\*. In other words, because of its proximity to the filament, the grid exercises a powerful control over the plate current. Its nearness to the filament makes it extremely efficient in attracting or repelling electrons, whereas its open mesh nature allows most of the electrons to pass through and reach the plate.

Because of the almost negligible inertia of electrons, this grid control has a very important consequence. If, for any reason the potential of the grid

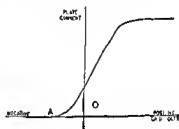


FIG 104 Graph showing the variation of plate current in a triode vacuum tube with variable grid and constant plate potentials

\* From the ratio  $\frac{30}{8.25}$  or 2.5, we obtain what is called the *amplification factor* of this tube.

rapidly oscillates above and below a mean value, fluctuations of the same frequency will occur in the plate circuit

**88 Generation of Undamped Oscillations** — Suppose a circuit is arranged as in Fig 105. It will be noticed that the loop  $RLC$  contains an inductance and a capacity, and consequently, if the resistance is low, has a natural frequency of electrical oscillations given by  $f = \frac{1}{2\pi\sqrt{CL}}$ . If, for

any reason a movement of charges is started in such a circuit and, in consequence, a small charge is given to the condenser, this loop should oscillate with this frequency. If such a circuit were an

independent, separate unit, and not part of an arrangement like Fig 105, these oscillations would be very feeble and would rapidly die out after the manner shown in Fig 96. In Fig 105, however, one side of the condenser of this oscillating circuit is joined to the grid of a triode. If, therefore, oscillations are started in the loop  $RLC$  (and even the closing of a switch can cause an initial electrical disturbance), the potential of the grid will change with the frequency of the oscillations. These rapid changes in grid

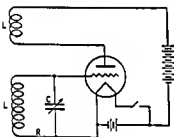


FIG 105 Circuit to illustrate the principle of retroaction and the use of a tube in generating high frequency currents

potential cause equally rapid changes in the plate circuit and, therefore, in the coil  $L_1$  inserted in this circuit.

If now, the coil  $L_1$  is placed near the coil  $L$ , that is, is coupled with it, electromotive forces of the same frequency as the frequency of the plate current changes are induced in  $L$ . These electromotive forces (if the coils are suitably wound with respect to each other) reinforce the oscillations originally started in the circuit  $RLC$ . The reinforced oscillations cause greater potential changes in the grid, hence changes of greater magnitude in the plate current hence induced electromotive forces of still greater intensity in the original oscillating circuit. There is, therefore, a cumulative effect which results in the maintenance of continuous oscillations. It is possible to increase the effect of this induct on sufficiently to make full

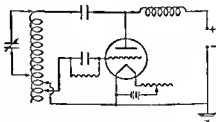
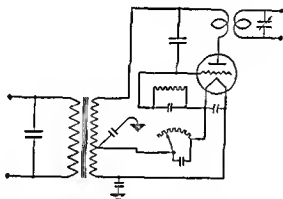


FIG 106 Connections for the Hartley oscillator

compensation for ohmic and other losses in the circuit so that the system behaves as if it possessed zero resistance, and an oscillation once started in it, persists" (Appleton)

By this principle of retroaction *continuous* undamped oscillations are maintained. In actual practice there are many different circuits employing this principle in one way or another. Figure 106, for example, shows the connections for a Hartley oscillating circuit one which has been extensively used. Figure 107 is a somewhat simplified diagram of the circuit used in a commercial "short-wave" oscillator, made by Siemens Reiniger-Werke, which is especially designed for use in high frequency therapy.



*Adapted from diagram by Siemens-Reiniger-Werke*

FIG 107 Somewhat simplified connections of the Ultratherm high frequency oscillator

**89 Diathermy with Undamped Oscillations** — Tube circuits are now used in much of the modern high frequency equipment in hospitals. In the inductotherm of the General Electric X-Ray Corporation, for example, a tube oscillator operating at a frequency of 12 million cycles per second is used. High frequency currents are passed through an insulated flexible cable which may be wound around or placed upon various parts of the body. The tissue in the immediate neighborhood of the cable is then heated as a result of induced currents.

In surgical diathermy, also, tube circuits are of great importance. Laboratory workers who "play" with high frequency currents of the continuous type soon find out that if the hand or any other part of the body touches the oscillating circuit, there is a slight spark accompanied by a burn at the spot where the spark strikes the flesh. This burn is made evident not only by the unpleasant sensation but also by a smell of seared tissue. By having a

metallic electrode suitably connected with the high frequency circuit, surgical use can be made of such burns in cauterizing and in coagulating tissue. In urology, for example, high frequency electrodes, themselves comparatively cool, are regularly used in surgical treatment.

**90 The Generation of Electric Waves** — From his elementary work in physics the student will recall that, if a particle at the end of a line of elastically connected particles is made to oscillate, a wave disturbance moves along the line. In general waves spread out from a vibrating source in any medium in which the particles are so connected that a displacement of a particle disturbs its neighbor. Moreover,  $\lambda$  the wave length,  $f$  the frequency of the oscillating source, and  $v$  the velocity of the wave disturbance are connected by the fundamental wave equation

$$v = f\lambda$$

or

$$\lambda = \frac{v}{f}.$$

Consider now the rapid high frequency currents which take place in a coil such as  $L_1$ , Fig. 102. When a current flows in a wire, it is surrounded by a magnetic field, the direction of the magnetic lines depending on the direction of the current. The oscillating currents in the coil  $L_1$ , therefore, give rise to an oscillating magnetic field about the coil. But, whenever we have a varying magnetic field, an induced E M F results. The rapidly changing magnetic field, therefore, gives rise to a changing E M F of the same frequency. Now Maxwell, the English physicist who was the real founder of wireless telegraphy, postulated that, even in a vacuum, such an E M F causes currents which he named *displacement currents*. According to Maxwell's ideas, these displacement currents have a magnetic field associated with them just like ordinary conduction currents in a wire. The varying magnetic field due to the displacement currents then gives rise to new induced E M F's, these in their turn, cause more displacement currents, and so the process continues with the result that an electromagnetic disturbance is propagated from the original region of oscillating currents. All this Maxwell put into mathematical equations by means of which he predicted that the velocity of the electromagnetic disturbance in free space should be the same as that of ordinary light, that is, about  $3 \times 10^{10}$  cm per sec.

Experimental verification of the truth of Maxwell's prediction was given in 1887 by Hertz, who showed that electric waves were generated by an oscillating circuit of the kind shown in Fig. 98, that these waves had many of the properties of light waves and traveled with the same speed. It is not easy to form a picture of electromagnetic waves but the following ideas will

perhaps give some help. From what has been stated above it follows that (1) at any given point in space, as time goes on the electric field and the associated magnetic must change their direction with a frequency which is the same as that of the original oscillating circuit, and (2) at any given instant, places where the electric field (or the magnetic) is in one direction must alternate with other places where this field is in the opposite direction. In other words, there is the periodicity in time and in space which characterizes a wave motion.

**91 Wave Lengths** — Waves generated as a result of electrical oscillations have an extremely wide range of wave lengths. Waves as short as a fraction of a millimeter and as long as several miles have been generated in this way. In radio almost the whole range is utilized in some way or other. On the dial of a common type of radio, one finds three bands, the standard broadcasting region with wave lengths ranging from 200 meters or less to nearly 600 meters, a medium region ranging from approximately 45 meters to nearly 200 meters, and the short wave region with wave lengths extending from about 12 meters to 45 or more. In radar, wave lengths a few centimeters or even millimeters in length are used. In the oscillator to which Figure 107 applies, the wave length of the emitted radiation is 6 meters. In physical therapy such equipment is sometimes referred to as "short wave."

The particular kind of electric waves used is often described by giving frequency rather than wave length, the two being connected by the fundamental wave equation  $v = f\lambda$ . Thus, since the velocity of all electromagnetic waves is  $3 \times 10^8$  meters per second, a wave length of 300 meters corresponds to a frequency of  $\frac{3 \times 10^8}{300}$ , or  $10^6$ , or 1 million, or 1 megacycle per second.

It will be recalled that in sound a note is invariably described by giving its frequency, and it will be seen in the next chapter that a particular kind of ordinary light is usually described by giving the corresponding wave length in a standard medium like air.

The name electric waves is restricted to those generated by oscillations in an electric circuit. They are a particular kind of electromagnetic waves and are of the same fundamental nature as many other types of radiation, such as infrared, ultraviolet and visible light, x-rays and gamma rays from radioactive materials. Differing widely in their properties because of differing wave lengths, all these radiations are periodic electric and magnetic disturbances which travel in free space at the same velocity. In the next and subsequent chapters we shall discuss in detail all these types of electromagnetic waves.

## PROBLEMS AND QUESTIONS

1 A charged condenser is discharged through a spark gap (1) What is the nature of the discharge current? (2) On what does the intensity of the discharge current depend?

2 When a condenser discharges through a low resistance and oscillations result, explain in what way the frequency of the oscillations depends on the capacitance of the condenser

3 Describe a simple arrangement for obtaining damped high frequency currents Explain how (1) the frequency, (2) the intensity can be altered

4 High frequency oscillations are set up in a circuit of very low resistance containing a condenser of capacity 0.001 microfarad and an inductance of 0.00002 henry Calculate the frequency of the currents *Ans*  $1.12 \times 10^6$

5 If electric waves are radiated from the circuit described in question 4, calculate the wave length of the waves *Ans* 263 meters



## CHAPTER IX

### LIGHT VISIBLE AND INVISIBLE

For many years after their discovery by Roentgen in 1895, the exact nature of x-rays was a subject about which there was much speculation. Although Roentgen himself thought of the new rays as a wave phenomenon, it was not until 1912 that conclusive evidence concerning their nature was given. In that year, however, as a result of the work of Laue, assisted by Friedrich and Knipping, it was experimentally demonstrated that the phenomenon of interference could be obtained with x-rays, and that consequently they were without doubt a form of wave motion. The pioneer work of these men at

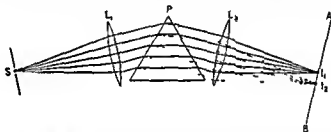


FIG. 108 The optical arrangement in a prism spectrograph

once led to methods of measuring the constituent wave lengths of a beam of x-rays. Before discussing this question in detail, it is desirable to make further reference to the particular kinds of electromagnetic waves we classify as (a) ordinary light waves (by means of which we have the sensation of sight), (b) infrared, and (c) ultraviolet.

**92 The Spectrograph** — The student will recall the familiar facts about the visible spectrum. When a beam of white light passes through a prism, a spectrum ranging from red to violet is formed, because red light is deviated by the prism less than yellow, yellow less than green, green less than blue, and blue less than violet. A common arrangement for obtaining a focused spectrum on a screen or photographic plate is shown in Fig. 108, where *S* represents a narrow slit illuminated by the light source to be examined and *L*<sub>1</sub> is a collimating lens placed at its focal distance from the slit so that a beam

of parallel rays emerges and falls on the prism,  $P$ . The light emerging from the prism is collected by the lens  $L_2$  and focused on the screen or plate  $AB$ . Since each kind of light is deviated a different amount by the prism, there are as many emergent bundles of light as there are kinds in the original beam, and hence a corresponding number of focused images on the screen. In the figure  $I_1$  and  $I_2$  there are two such images.

When a photographic plate is used, permanent records, such as illustrated in Fig. 109 and Fig. 110 are obtained, the whole arrangement constituting a

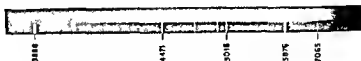


FIG. 109 The continuous spectrum emitted by an incandescent lamp or any white hot solid, with helium spectrum superimposed

spectrograph. If the source of light is an incandescent lamp, there are so many constituent wave lengths that the images overlap giving a continuous spectrum such as Fig. 109. Many sources however, such as luminous hydro-

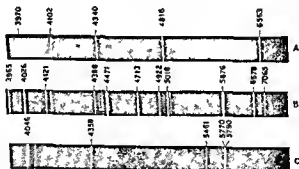


FIG. 110 Line spectra in the visible region emitted by a, hydrogen; b, helium, and c, mercury vapor

gen or mercury vapor, emit only isolated wave lengths, giving spectra like Fig. 110 where each spectral line corresponds to a definite wave length.

**93 Measurement of Wave Length** — The determination of the actual wave lengths of these spectral lines is an important practical problem. Every method is based on the principle of interference, that is, the principle that when two (or more) light beams are superimposed, the resultant may be either light or darkness, depending on the phase difference between the

disturbances. If two beams are exactly in step, crest meeting crest, trough meeting trough, there is a resultant maximum disturbance, or brightness, if the two are exactly out of step, crest of one meeting trough of the other, there is darkness. One such method for evaluating wave lengths, which the student is asked to recall because of its connection with x-ray work, makes use of the diffraction grating.

If water waves strike a barrier with an opening such as  $M$ , Fig. 111*a*, which is small in comparison with the wave length of the waves, the disturbance spreads out from the opening in all directions. Similarly, if a beam of monochromatic light strikes a narrow opening, of width say  $\frac{1}{1000}$  mm, as in

Fig. 111*b*, the light too spreads out (or is diffracted) over a wide angle. Now

consider a surface on which there is a large number of small openings, spaced at regular intervals, as in a transmission grating. If a beam of parallel rays of monochromatic light is incident on such a grating, somewhat as shown in Fig. 112, light spreads out from each opening. If this diffracted light falls on a lens  $L$ , at every point in its focal plane there will be a superposition of as many little bundles as there are openings in the grating. Figure 112\* shows the superposition at  $P$  and at  $Q$ , of the bundles in two directions.

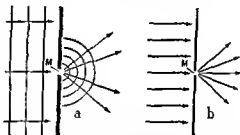


FIG. 111 When plane waves or parallel rays strike an obstacle with an aperture of width comparable with the wave length, the wave disturbance spreads out from the aperture.

It is important to note that since the rays which are superimposed at any one point are all incident on lens  $L$  in the same direction, the path difference, that is, the distance one ray travels farther than its neighbor, is the same for each successive pair of rays. Thus, using Fig. 112, or the enlargement in Fig. 113, ray 2 travels a path from the grating to  $Q_1$  which is greater than the path for ray 1 by  $AB$ , ray 3 a path greater than ray 2 by  $CD = AB$ , and so on for every successive pair. Moreover, the actual magnitude of this path difference is easily seen to be  $s \sin \theta$ , where  $s$  is the grating element, that is, the distance  $EA$  or  $AC$  from one opening to the next, and  $\theta$  is the angular distance of the point  $Q_1$  from the original direction of the beam of light. This path difference, then, steadily increases, the greater the angle  $\theta$ .

\* Although in an actual grating there may be several thousand small openings in this figure only a few are shown, in order to make clear the underlying ideas.

Suppose, now, that at a value of  $\theta = \theta_1$  the path difference between successive rays is exactly one wave length, that is, that  $s \sin \theta_1 = \lambda$ . Then the rays for this particular direction when superimposed all arrive in step or in phase, reinforcing each other, and a very bright image results. Other bright images

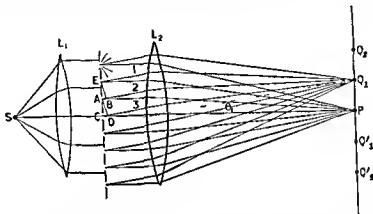


FIG. 112 Optical arrangement for obtaining a spectrum with a transmission grating

are obtained in the special directions  $\theta_2, \theta_3, \theta_4$ , etc., where  $s \sin \theta_2 = 2\lambda$ ,  $s \sin \theta_3 = 3\lambda$ ,  $s \sin \theta_4 = 4\lambda$ , etc. With the arrangement shown in Fig. 112, then, the original beam of monochromatic light gives rise to a central bright image or order at P (where the rays reinforce because the path difference between any two is zero and again all are in step), first order images on either side of P, at Q and Q', corresponding to the angle  $\theta_1$ , second order images at Q<sub>2</sub> and Q'<sub>2</sub>, corresponding to  $\theta_2$ , and possibly higher orders.

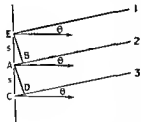


FIG. 113 Enlargement of a portion of Fig. 112

If the original beam, instead of being monochromatic, consists of a mixture of wave lengths, we obtain a series of first order images, one for each constituent wave length, and another series of second order images, or, the light is spread out into a first and second order spectrum (and possibly higher orders). If, for each image, in a spectrum, we measure the corresponding  $\theta_1$  and  $\theta_2$  (as we can readily do by means of a spectrometer) then the wave lengths can at once be found, from either of the relations

$$\lambda = s \sin \theta_1 \quad \text{or} \quad 2\lambda = s \sin \theta_2,$$

provided that the magnitude of  $s$  is known

Instead of a transmission grating, a reflection grating is often used. A

good reflection grating is made by ruling, with a diamond point and a dividing engine, a series of regularly spaced grooves on polished speculum metal. If such a grating is made on a plane surface and a beam is incident as in Fig. 114, the light is diffracted and bundles of rays in the same direction are superimposed by a lens at  $Q$  as with the transmission grating. For exactly the same reason as given above, spectra are obtained, and a complex beam is analyzed into its constituents. In another very important type of reflection grating, rulings are made on a concave surface. With this type, it is possible to obtain superimposed bundles without the use of a lens.

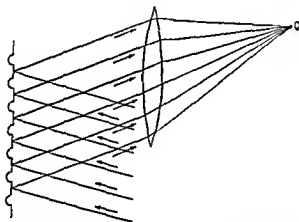


FIG. 114 To illustrate the principle of a plane reflection grating

94. **The Angstrom and Millimicron** — Measurements obtained with gratings (and other means) show that the visible spectrum contains wave lengths ranging from about 0.00004 cm at the violet end to slightly greater than 0.00007 cm at the red end. When isolated wave lengths emitted by different substances are measured, we obtain such values as 0.00007682 for a potassium red line, 0.00006563 for a hydrogen red line, 0.00005790 and 0.00005770 for two bright mercury yellow lines, 0.00005461 cm for a very bright mercury green, and so on for literally tens of thousands of measured lines. Since these wave lengths are so very small, for convenience, instead of using a centimeter as unit of length, the *angstrom* and the *millimicron* are often used. An angstrom (called after Angstrom, a Swedish pioneer in spectroscopy) is equal to  $10^{-8}$  cm. A micron being equal to  $\frac{1}{1000}$  mm, a millimicron is  $\frac{1}{1000}$  of a micron or  $10^{-6}$  mm, or  $10^{-7}$  cm.

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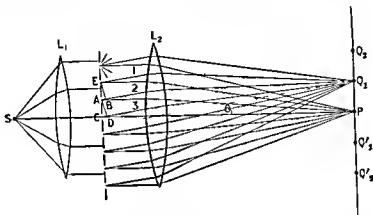


FIG 112 Optical arrangement for obtaining a spectrum with a transmission grating

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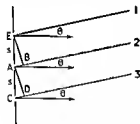


FIG 113 Enlargement of a portion of Fig. 112

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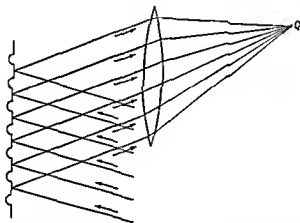


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The above wave lengths may then be written in angstroms as 7682, 6563, 5790, 5770, 5461, and in millimicrons or  $m\mu$  as 656.3, 579.0, 577.0, 546.1

**95 The Infrared** — The student will recall that the spectrum does not end with the region where the eye ceases to have the sensation of red. Beyond the visible red is an invisible region of longer wave lengths, called the *infrared*, a region which may readily be made evident by the rise in temperature of a sensitive instrument such as a thermopile or radiometer or even the blackened bulb of a thermometer. Infrared rays are sometimes called heat rays because of this development of heat when they are absorbed, but the name is misleading, since the energy of visible and other electromagnetic waves on absorption is also changed into heat.

At least part of the infrared region may be examined photographically, because in recent years, emulsions have been developed which are sensitive to part of this region. Figure 115, for example, is a photograph of the spectrum

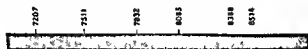


FIG. 115 Spectrum in the near infrared

of the iron arc showing wave lengths extending beyond 8500 angstroms. Apart altogether from spectrum work, infrared photography has important applications although most of them are not of special interest to the medical student. Many of the applications arise from the fact that infrared rays, because of their longer wave lengths, are less scattered by fine particles of dust or fog in the atmosphere, and so are much more penetrating. Details of distant landscapes, for example, stand out with remarkable clearness. Indeed mountain ranges have been photographed at a distance of several hundred miles, and from airplanes well over four miles high, infrared photographs showing details over a wide range of terrain, are taken.

**96 Range of Infrared Radiation** — The extent to which a spectrum extends into the infrared depends on the nature of the source, primarily on its temperature. There are few people who are not familiar with the fact that if in a dark room, the temperature of a solid, like a piece of iron, is gradually raised, it remains invisible for a time but, after further heating, it becomes at first reddish in color, and finally, if made hot enough, "white hot." This fact illustrates a fundamental law of radiation which states that as a body becomes hotter and hotter it radiates an excess of shorter and shorter wave lengths. Stated otherwise, it means that the wave lengths of the region



in which the intensity of the radiation from a source is a maximum are shorter, the higher the temperature of the source. For example, an electric iron at  $300^{\circ}\text{C}$  or  $400^{\circ}\text{C}$ , invisible in the dark, although too hot to touch, emits infrared radiation with a maximum intensity in the region 40,000 to 50,000 angstroms. The same iron, if heated to  $700^{\circ}$  or  $800^{\circ}\text{C}$ , would become reddish in appearance because it now emits some visible light at the red end of the spectrum, the region of maximum intensity shifting to 20,000 or 30,000 angstroms. With an incandescent source as hot as the sun, the region of maximum intensity is in the visible part of the spectrum, being in the neighborhood of 5000 angstroms, or a trifle less. It should not be forgotten, however, that such a source also emits considerable infrared radiation.

In therapy, the infrared region is sometimes divided into the near infrared, extending from the red end of the visible spectrum to about 14,000 or 15,000 angstroms, and the far infrared, comprising still longer wave lengths. Similarly, sources used in infrared therapy are sometimes classified either as short wave or luminous emitters, like incandescent lamps, or as long wave sources, such as dull red or non luminous heaters.

In considering the choice of a source for infrared therapy, a student should bear in mind that any biological action from such radiation is due to a rise in temperature of tissue, a factor which depends primarily on the absorption of radiation. Research workers in this field, like Cartwright, Forsythe, Adams and Luckiesh, have shown that infrared in the long wave length region is absorbed by a very thin superficial layer of tissue, causing a marked feeling of warmth on the part of an individual on whom such radiation falls. On the other hand, maximum transmission by tissue occurs for wave lengths in the neighborhood of 11,000 angstroms. Hence, if it is desired to have infrared penetrate tissue to any extent, a source emitting maximum intensity near this region should be used. Curves giving the intensity distribution of the radiation from a 500 watt CX lamp show that the region of maximum energy is around 9000 or 10,000 angstroms. Hence it is a fairly good source if penetration is desired. Since such a lamp also emits some energy in the much longer wave lengths, it is sometimes wise to reduce superficial absorption with the resulting uncomfortable feeling of warmth. This can be done by placing a water cell between the lamp and the patient, since a 1 cm. layer of water almost completely absorbs the long wave lengths beyond 14,000 angstroms. Ordinary glass, it may be noted in passing, is fairly transparent in the near infrared, although its transmission decreases rapidly beyond 30,000 angstroms. In all media the amount of absorption, of course, depends on the thickness of the absorbing layer.

**97 The Ultraviolet** — Beyond the violet end of the visible spectrum, another invisible region, the *ultraviolet*, is readily revealed either by photography or by means of the fluorescent light emitted when ultraviolet rays fall on certain substances. Figure 116 is a photograph of the spectrum of mercury



FIG 116 The near ultraviolet spectrum of mercury vapor

vapor, in which the wave lengths of most of the spectral lines are in the ultraviolet region. Since ordinary glass completely absorbs wave lengths shorter than about 3200 angstroms (see Fig 117), a spectrograph for the analysis of the ultraviolet must use prisms and lenses of some other material. By far the commonest is quartz, which is transparent to wave lengths as short



FIG 117 Spectra of mercury vapor (a) without filter of ordinary window glass (b) with such a filter

as 1850. The use of fluorite extends the limit to about 1200 and of lithium fluoride to about 1083. In this region absorption difficulties become very great. Air itself, at atmospheric pressure, because too opaque for the investigation of wave lengths in the

extreme ultraviolet and vacuum spectrographs with concave gratings, become necessary. With this type of instrument wave lengths as short as 40 angstroms have been photographed.

**98 Sources of Ultraviolet** — Attention is directed to the following sources, of special interest in radiology:

(a) *Any open arc*, such as that between the carbon rods of a projection lamp, or between any two metal rods. If the carbon rods are impregnated with various compounds, the intensity distribution in the spectrum of the emitted light may be altered, some parts being enhanced more than others, depending on the nature of the compound used.

(b) *The Sun*. Under the most favorable conditions, such as high noon in midsummer, the shortest wave length in the solar spectrum is in the neighborhood of 2950 angstroms. Ordinary window glass, as we have already noted, will transmit nothing shorter than about 3200.

According to figures given by F. S. Brackett of the Smithsonian Institute, of the total solar energy radiated, from 1 to 5 per cent is in the ultraviolet,

from 41 to 45 per cent in the visible, and from 50 to 58 per cent in the infrared

The amount of indirect radiation from the sky, as distinguished from the direct rays of sunshine, depends on the wave length, but for the region 2900–3200 *it may exceed that of the direct beam*

(c) Sun Lamps If an incandescent lamp, or any other kind enclosed in a transparent envelope, is to be used as a substitute for the sun, as far as ultraviolet is concerned, the bulb or envelope must be made of quartz or of special kinds of glass transmitting wave lengths as far, at least, as 2950. The source of light must also radiate wave lengths of appreciable energy as short as this limit. An ordinary lamp with a tungsten filament is not of much use as a source of ultraviolet because, as we have already seen in Section 96, although any hot body radiates a continuous spectrum, the region in which maximum energy is radiated depends on the temperature. In the solar spectrum, this region is in the neighborhood of 5000 angstroms. Since this corresponds to a temperature of about 6000° absolute, and since in the most powerful incandescent lamps, maximum temperatures are only about 3350° absolute, we could not expect ordinary lamps with tungsten filaments to reproduce the solar spectrum. The Mazda C-4 lamp is a special one designed for operation at a filament temperature exceeding 3350°. The emitted radiation from this extends into the ultraviolet nearly, but not quite, as far as the solar spectrum.

So called sun lamps usually make use of some kind of arc in mercury vapor. Figure 116 is the spectrum of an electric discharge produced by high frequency currents in a quartz tube containing mercury vapor at low pressure. The source was not a sun lamp, but it emphasizes the fact that the spectrum of an arc in mercury vapor at low pressure consists largely of isolated wave lengths extending well into the ultraviolet.

In the S 1, one of the earlier sun lamps, there is an arc between tungsten terminals in an atmosphere of mercury vapor. The spectrum is a combination of a continuous band in the red and green regions, plus the mercury spectrum, which is transmitted by the special glass of the envelope, to possibly 2000 angstroms. In another sun lamp, the S 4, a mercury arc takes place in a small quartz inner tube, the outer envelope being again made of special glass.

(d) Other lamps The AH-6 lamp is a powerful 1000-watt source of both luminous radiation and near ultraviolet, consisting fundamentally of a high pressure mercury arc in an inner quartz tube, with an outer glass envelope and an arrangement for continuous water cooling. At high pressures, the

spectrum of discharges in mercury vapor is less confined to sharp isolated wave lengths

By way of contrast to the AH-6, reference is made to the 30-watt *germicidal lamp*, which carries a comparatively feeble discharge through mercury vapor at low pressure, and has an outer envelope transmitting wave lengths to at least 2500 angstroms. In this kind of lamp, which is sometimes designated as "cold" because of the low power consumption, there is a high concentration of ultraviolet energy in the isolated wave length 2537.

In principle the modern fluorescent lamp is essentially the same as the germicidal type. In the fluorescent lamp, the inner walls are coated with suitable phosphors which, under the stimulus of mercury wave lengths, emit fluorescent light.

**99 The Use of Ultraviolet in Medicine** — Reference will be made to three ways in which ultraviolet light is of importance to the medical student (1) as an agent for the production of erythema, (2) as an agent for killing bacteria, and (3) as an agent for the manufacture of vitamin D. As always, in this book we are concerned primarily with basic physical ideas.

Few people are unaware of the effect of sunlight on the skin. To examine this effect scientifically some relation must be found between the biological effect — the reddening of the skin followed by tanning — and the intensity and the quality of the radiation. As far as quality goes, examination of the effect of different wave lengths shows that ultraviolet light is necessary for tanning, and that, if we restrict ourselves to sunlight, the most effective range is between 2900 and 3100 angstroms. It is, therefore, only the extreme short wave length end of the solar spectrum which is useful. In fact, the useful component is so near this end that during the shortest days of the year the erythema-producing component is negligible.

To examine the effect quantitatively first of all some biological reaction must be agreed on as a standard, or as near a standard as is possible in biological work where individuals differ so much. The standard effect commonly adopted is the *minimum perceptible erythema*, or the M P E, which may be defined as a "barely perceptible reddening of an average untanned skin." The "dose" necessary to produce an M P E must next be determined. If there were a single constant source of ultraviolet radiation, this would involve only a determination of the time necessary to cause an M P E. For example, the Mazda S 1 sunlamp, at a distance of 30 inches, produces an M P E in from 5 to 7 minutes. But everybody does not use Mazda S-1 lamps, and even the layman knows that the useful ultraviolet content of the sun varies tremendously with the season of the year. It is therefore necessary

to have some means of measuring fundamentally, the actual intensity of the ultraviolet component of the radiation which is effective in producing erythema.

Over a wide range of wave lengths, extending from the infrared to well down in the ultraviolet, intensity may be measured by any sensitive detector of the rise in temperature which results from the absorption of radiant energy. For this purpose the thermopile, the thermocouple, the bolometer, and the radiometer are all used. In using an instrument like the thermocouple, one may either measure the intensity of the beam as a whole, or the beam may be separated into its constituent wave length, and the relative intensities measured by moving the thermocouple along the spectrum. In the latter case, some form of amplification is desirable.

If the specific problem is an examination of the intensity of the erythema-producing rays, the remainder of the rays can be removed by a suitable filter. This is what is effectively done when use is made of the *photoelectric effect*, a phenomenon which may be demonstrated by the following simple experiment.

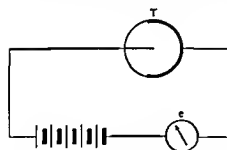


FIG 119 Simple arrangement of photoelectric cell *T* with galvanometer and battery

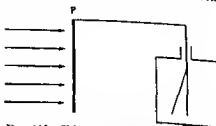


FIG 118 When light of suitable wave length falls on a zinc plate *P* joined to the insulated part of an electroscope the electroscope if negatively charged loses its charge

Suppose an insulated zinc plate *P*, Fig 118, is joined to the knob of an electroscope, and that the system is negatively charged. With proper insulation the leaf of the electroscope remains for some time with deflection unchanged. If, however, light from an arc lamp is allowed to fall on the metal plate, the electroscope leaf quickly falls. If the system is positively charged, no such discharge takes place. The discharge when the

plate is negatively charged is caused by a photoelectric emission of electrons from the surface on which the light is incident. A photoelectric cell is a refined device making use of this principle. In one form a highly evacuated tube *T*, Fig 119, has an anode consisting of a single wire or ring projecting into the tube, and a cathode, a large area of a metal surface spread over a part of the inside wall. When such a tube is inserted in a circuit as shown in Fig 119, and light falls on the metallic surface, a current is indicated by the gal-

vanometer  $G$  because of the photoelectric emission of electrons from the surface

In connection with the relation between this current and the nature of the incident light, two important facts should be noted (1) The magnitude of the photoelectric current is directly proportional to the intensity of the incident light. The galvanometer reading, therefore, is a measure of the intensity of the light. (2) For any given metallic surface, wave lengths longer than a certain critical value do not cause any photoelectric emission. For example, if the above experiment is repeated with a piece of red glass in front of the zinc plate, the electroscope is not discharged, because for zinc the critical wave length is about 3020 angstroms, and the light transmitted by a piece of red glass includes little shorter than 6000 angstroms.

The value of the critical or threshold wave length depends markedly on the nature of the surface. Thus, for the element caesium it is 6810 angstroms, for sodium 5830, for aluminum 4770, for silver 3250, for cadmium 3140, and finally for an alloy of cadmium and magnesium 3350. For the examination of the intensity of the erythema production component of solar radiation, a photoelectric cell with a cadmium-magnesium surface is particularly useful, because "its spectral sensitivity is such that it responds to the ultraviolet energy of various wave lengths approximately in accordance with their effectiveness in producing erythema or sunburn." It should be borne in mind that the region of wave lengths for which a photoelectric surface has a maximum sensitivity is somewhat below the critical wave length. For a cadmium-magnesium surface, the greatest sensitivity is around 2800 angstroms. In the production of erythema the most effective wave lengths are in the region 2950 to 3000. Note (see Fig 116) that in the mercury spectrum, a fairly strong line occurs at 2967.

**100. The Finsen** — In considering any unit of dosage relating to radiation, the reader must distinguish between *intensity* and total radiant energy. Intensity is measured by the time rate at which energy passes through unit area, or by what is often called the *flux of radiant energy per unit area*. If our interest is in illumination and vision, we are concerned only with that portion of the total radiation which is of value for vision, or in what is called *luminous flux*. If our interest is in the production of an erythema, our concern is with erythema-producing radiation. In this field, a unit of intensity has been standardized by the Illuminating Engineering Society and the International Commission on Illumination, although it has not yet received widespread use. It can best be explained by a brief reference to work done by Luckiesh and collaborators at the Lighting Research Laboratory of the General Electric Company.

The unit of erythema-producing flux is called the *E-viton*, the corresponding unit of intensity being, of course, 1 *E-viton* per sq cm. For this unit of intensity the name *finsen* has been suggested by Luckiesh in honor of Finsen, a Danish pioneer in light therapy.

By definition, 1 *finsen* is a flux of 10 microwatts per sq cm of radiant energy of that particular wave length which has a maximum effect in producing erythema. As we have already indicated, this wave length is close to 2967 angstroms. In order to find the number of microwatts per sq cm of any other wave length which is equal to 1 *finsen*, use must be made of a curve such as that given in Fig 120. Such a curve, obtained by experiments

of Luckiesh and other workers, shows the relative effectiveness of different wave lengths in the production of erythema. Suppose, to take an example, that we wish to find the value of the *finsen* for wave length 3022 angstroms. On consulting this curve we note that, when the effectiveness of 2967 is taken as 1, that of 3022 is only 0.55. For this wave length, then, the *finsen* has the value  $10/0.55$  or about 19 microwatts per sq cm.

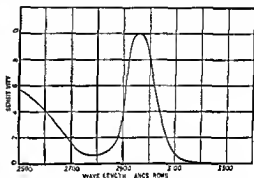


FIG 120 Curve showing relative effectiveness of different wave lengths in the production of erythema. (After Luckiesh and co-workers.)

Dosage, as we have seen, refers to the total amount of energy of the useful wave lengths delivered at any given place. Evidently the total energy delivered depends on (a) the intensity of the useful components, and (b) the time of application. In the case of erythema producing radiation, the unit of dosage is either a *finsen* second, or a *finsen*-minute, or a *finsen* hour. Actually, *finsen* hours are used a great deal.

General Electric workers have published curves showing the number of *finsen*-hours of erythema-producing solar radiation received on a horizontal plane each month for a period of four years. Their results give numbers ranging as low as 27 for December to 452 for June. It is interesting to note that the highest intensity recorded during the whole four years' period was about 4.2 *finsens*. "This," these workers stated, "will cause a M P E on average untanned skin in about 10 minutes." According to this statement, the dose causing the M P E is  $4.2 \times 10/60$ , or 0.7 *finsen*-hour. This is in agreement with the statement that by exposing several men to sunlight in the month of July, the average M P E dose was found to be  $\frac{2}{3}$  of a *finsen* hour.

It is interesting to note that the *total* erythema producing flux from a 60-watt Mazda CX lamp is 140 E-vitons, from a 500-watt CX lamp, 3200 E vitons, and from the 440-watt S-1 lamp, as much as 70,000 E-vitons

**101 Germicidal Effect of Ultraviolet** — A second important application of ultraviolet radiation is its use for the destruction of bacteria. In this, as in any other application, one of the first problems is to examine what

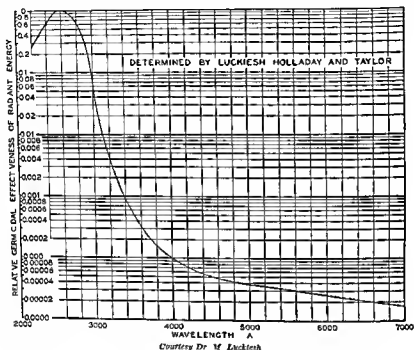


FIG. 121 Graph showing the relative effectiveness of different wave lengths in killing B. Coli

wave lengths or range of wave lengths are most effective. To some extent the answer to that problem depends on the nature of the bacteria to be destroyed. There is general agreement, however, that the wave lengths which have a maximum bactericidal effect are in the neighborhood of 2600 angstroms. Note, for example, the curve due to Luckiesh, Halladay and Taylor, reproduced in Fig. 121, which shows the relative effectiveness of a wide range of wave lengths for killing B. Coli.

The occurrence of a maximum germicidal effect for wave lengths near 2600 angstroms is extremely fortunate because the most intense wave length in the complete ultraviolet spectrum of mercury is at 2537 angstroms.



Moreover, when an electric discharge takes place in a tube containing mercury vapor at low pressure, as much as 95 per cent of the total ultraviolet energy appears in this wave length. It follows that an almost ideal germicidal source of ultraviolet radiation is to be had in a low pressure mercury vapor lamp, provided its walls are transparent to wave length 2537. This condition is readily fulfilled by making the containing tube either of quartz or of special kinds of glass such as Cortex. Such lamps, similar in operation to the familiar fluorescent tubular kind, are on the market. For example, one consuming only 15 watts is suitable for installation in a refrigerator where it is effective for the prevention of the formation of mould.

TABLE VII—RANGE OF ELECTROMAGNETIC WAVE LENGTHS

Kind	Longest	Shortest
Electric	20+ miles	0.22 mm
Infrared, far	0.4 mm	15,000 angstroms
Infrared, near	15,000 angstroms	7,700 angstroms
Visible	7,700 angstroms	4,000 angstroms
Ultraviolet, near	3,900 angstroms	2,900 angstroms
Ultraviolet, far	2,900 angstroms	1,800 angstroms
Ultraviolet, extreme	1,800 angstroms	40 angstroms
X-rays	500 angstroms	0.05 angstrom
Grenz X rays	5 angstroms	1 angstrom
Diagnostic X rays	0.3 angstrom	0.1 angstrom
Therapeutic X rays	0.1 angstrom	0.05 angstrom
Gamma rays	0.3 angstrom	0.006 angstrom

A comparison of a 300-watt, 115-volt mercury arc lamp with a 30-watt, 115-volt type designed for bactericidal purposes, emphasizes the importance of operation with mercury at low pressure. Although the power consumption of the first lamp is ten times greater than the second, measurements by Luckiesh show "that a 30-watt germicidal lamp can often be more effective in (germicidal) practice than a 300-watt quartz mercury arc." As already indicated, the reason lies in the fact that in a discharge at low pressure, almost all the ultraviolet energy is concentrated in wave length 2537.

The student should now understand why a sunlamp which, with its shortest wave length around 2800 angstroms is excellent for the production of erythema, is a poor source for germicidal use. It should also be apparent that, although sunlight has undoubtedly a germicidal effect on some organisms, the low pressure mercury vapor lamp transparent to 2537 radiation is a far more effective agent.

As far as dosage is concerned, special germicidal units should be developed, just as in the case of erythema-producing radiation. Much quantitative work

has been done by Luckiesh and others, but as units have not yet been finally standardized, discussion of details is omitted in this book. The student should note, however, that valuable information is provided if all persons using germicidal lamps record the power input of the lamp used, the time of application, and the distance of the lamp from the material radiated.

**102 Production of Vitamin D** — Ultraviolet radiation of selected wave lengths is of great importance in the production of vitamin D, the organic agent which promotes normal calcium metabolism. The absence of vitamin

D from a diet means imperfectly calcified bones and may give rise to rickets. A cure may be brought about by irradiation with ultraviolet light of suitable wave length. When the ergosterol in the skin absorbs the radiation, vitamin D is manufactured and subsequently gets into the blood stream, effecting the cure. The ergosterol is said to be activated.

There is evidence that the region of maximum efficiency for the production of vitamin D is about the same as for the production of erythema; hence in the region around 2800 or 2900 angstroms the erythema effect is an approximate measure of the anti-rachitic effect. But, it should be noted that, according to Luckiesh, "there are indications that energy in the region of 2500 and 2600 is anti-rachitic through the production of vitamin D. The use of germicidal lamps in poultry houses also yields some evidence in this respect."

### 103 Range of Electromagnetic Waves —

In section 91 it was pointed out that infrared, visible, and ultraviolet light belong to the same class as electric waves, all being electromagnetic in nature. Although we have yet to discuss x-rays and gamma rays from radium, two other kinds of radiation which must be included in the same category, it is convenient

at this stage to record the classification of wave lengths given in Table XII. It should be understood that there is nothing rigid about the short and long wave length limit in any particular group.

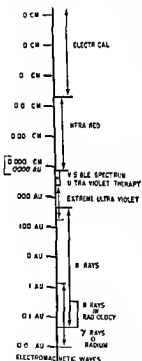


FIG. 122. Schematic representation of complete range of electromagnetic wave

## PROBLEMS AND QUESTIONS

1 (i) Describe fully how you would photograph the ultraviolet and visible spectrum emitted by any source of light. (ii) Compare the spectrum you would obtain with a carbon arc with that from a quartz mercury vapor lamp. (iii) If your source of light was sunlight, what would be the approximately shortest wave length recorded (in angstroms), (1) through an open window, (2) through a closed window of ordinary glass? In each case explain why no shorter wave lengths are recorded.

2 State three ways in which ultraviolet light is of importance in medicine. With respect to each state whether (i) wave length 2950 (i) sunlight, is a good or a poor agent.

3 An insulated zinc plate is joined to the leaf of an electroscope, the whole positively charged. When light from a bare arc lamp falls on the zinc plate, the electroscope does *not* lose its charge. Explain.

4 Explain the relation of 1 angstrom, 1 millimicron and 1 X U to the centimeter.

5 If the first order image of a certain wave length, obtained with a transmission grating on which the light is incident perpendicularly, is  $20^\circ$  from the central order, show how you would calculate the position of the second order image.

6 A transmission grating has 14,520 elements in 1 inch. Find, in angstroms, the wave length of monochromatic light which gives first order images  $19^\circ 42'$  from the central order. *Ans* 5890 angstroms.

7 Why is a low pressure, low power mercury lamp a more efficient germicidal lamp than a high pressure, high power mercury lamp? Assume each has a quartz container.

8 Why does a person feel warmer when near a 500 watt dull emitter of heat than when at the same distance from a 500 watt high temperature lamp?

9 A certain lamp emits a total erythema producing flux of 3000 F vitons. (a) Find the intensity (in finsens) of this type of radiation at a distance of 50 cm from this lamp assuming it radiates equally in all directions. (b) Find how long it would take to deliver, at this distance, an average M P E dose equal to  $\frac{2}{3}$  of a finsen hour. *Ans* 0.098; 7 hours.

## CHAPTER X

### GENERAL PROPERTIES OF X-RAYS

In section 40 it was pointed out that a beam of x-rays radiates from the focal spot of an x-ray tube. In this chapter we shall discuss some of the important properties of such a beam.

**104 Photographic Effect** — X-rays affect a photographic plate or film, or sensitized paper in much the same way as ordinary light. The speeds of different photographic emulsions vary, and, for the same plate, the speed varies with the kind of rays used.

**105 Fluorescent Effect** — X-rays excite fluorescence in certain substances on which they fall. By fluorescence we mean the emission of visible light which continues as long as the rays strike the substance. As it was the fluorescent property which led to the discovery of x-rays by Roentgen, it is of interest to quote a few sentences from a translation of a preliminary communication read by Roentgen, on Dec. 25, 1895, before the *Physikalisch-medizinischen Gesellschaft* of Würzburg: "If the electric discharge from a large Ruhmkorff coil is passed through a Hittorf vacuum tube, or through a sufficiently exhausted Lenard-Crookes, or similar tube, and if the tube is covered with a fairly close fitting envelope of thin black card, it will be found that a paper screen placed near the apparatus and covered with barium platinocyanide will become brightly luminous and fluorescent. It is immaterial whether the prepared side or the unprepared side is turned towards the apparatus. The fluorescence is still noticeable at a distance of two metres from the apparatus. It is easy to establish that the cause of the fluorescence proceeds from the discharge tube and from no other part of the electric circuit."

"The first remarkable feature about this phenomenon is that we have here an agent that can pass through a black card envelope which is impervious to the visible and ultraviolet rays of the sun or electric arc, and that this agent is capable of producing vivid fluorescence. The fluorescence of barium platinocyanide is not the only recognisable effect of the x-rays. Other bodies also fluoresce, as for instance the calcium compounds known as phosphor, also uranium glass, ordinary glass, caesopar, rocksalt, etc.

"Photographic dry plates are sensitive to x-rays, and this fact is of special

importance in many respects. It enables many phenomena to be recorded, thus making it easier to exclude deceptions and whenever possible I have checked by means of a photographic exposure every more important visual observation on the fluorescent screen."

In radiology two applications of the fluorescent effect of x-rays are made (1) in the use of a *fluorescent screen* for diagnostic purposes, and (2) in the use of *intensifying screens* for shortening exposures when radiographs are being made. There are few people nowadays who are not familiar with the shadow pictures which the roentgenologist so often studies when a patient is between the x-ray tube and the fluorescent screen. In the rapid x-ray chest surveys of large groups of people, which are frequently made for tuberculosis tests, use is made of fluorescent screens. By photographing the shadow picture of a person's chest and lungs which is thrown on a fluorescent screen by the x-ray tube, it is possible to make records at the rapid rate of about one person per minute.

Intensifying screens are used in standard photographic diagnosis, where a fluorescent screen is replaced by a sensitive plate or film in order to shorten the time of exposure. These screens, which are made of such substances as tungstate of calcium, are placed directly in contact with the sensitive emulsion on the photographic plate or film. Wherever the rays strike the screen, therefore, the bluish (fluorescent) light emitted (which is much more actinic than x-rays) acts on the emulsion and so shortens the exposure to a marked degree. A reduction as much as five- to tenfold is quite normal. Care must be taken to keep the screen clean, for particles of dust will absorb the visible fluorescent light and spot the plate. The exposure may be still further shortened by using films sensitized on both sides along with intensifying screens on each side of the film. "In actual use intensifying screens are mounted in rigid holders called cassettes, in order that perfect contact may be obtained between emulsion and screen" (Eastman Kodak Co.)

**106 Chemical and Dehydrating Effects** — X rays produce a discoloration of certain alkaline salts, liberate iodine from a solution of iodoform in chloroform, and change the color of certain substances such as barium platinocyanide.

**107 Biological Effects** — The burns which result from undue exposure to x-rays, the beneficial effects of the rays in curing certain skin diseases, the stunting of the growth of young animals, the production of injuries and of genetic changes in cells, the destruction of cells and the killing of eggs of the *Drosophila* fruit fly, the production of carcinogenesis and a possible germicidal

action on bacteria — these are some of the many examples of this important property concerning which more will be stated later

**108 Ionization Effect** — X-rays make the air through which they pass conducting, as may readily be shown by placing a charged electroscope almost anywhere near a tube. On sending a current through the tube it is at once observed that the leaf of the electroscope steadily falls until the whole charge

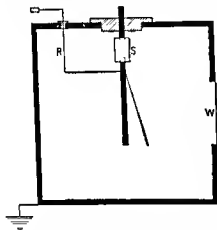


FIG 123 A simple electroscope for rough ionization measurements

has disappeared. The rays have ionized the air in the neighborhood of the electroscope to an extent which is proportional to the rate at which the leaf falls. Should the experiment be repeated a number of times, each time placing the electroscope at a greater distance from the tube, it would be found that the leaf falls more slowly the further it is removed from the tube. This indicates that the ionization and so the intensity of the beam of x rays at a local region is greater, the nearer the region is to the tube (Section 147.)

As the ionization property is the basis of the most accurate methods of esti-

matng dosage when x rays are used for treatment, the importance of this property cannot be too strongly emphasized. Later, details of suitable ionization chambers will be given. At this place, however, a simple form of electroscope which has been found useful may be noted (Fig 123). The leaf is attached to the usual metal support but this instead of ending in a knob outside the electroscope, is supported by means of the insulating bead of sulphur *S*. The whole is enclosed in an earthed metal chamber with a window *W* covered with very thin metal foil through which x-rays may pass. The electroscope is charged by means of a movable rod *R* which passes through an insulating support to the outside of the box.

**109 Penetrating Effect** — There are few people nowadays who are not familiar with the fact that x rays pass through fairly thick sheets of matter which we ordinarily call opaque. A piece of wood is almost as transparent to x rays as window glass is to sunlight. But thin layers of any substance are more transparent than thick, and some substances are more opaque than others, herein lies the basis of the familiar x-ray pictures. Radiographs are just shadow pictures, wherein detail is visible because of the unequal degree

to which different parts of the subject photographed absorb x-rays. There are in consequence corresponding differences in density on the plate or film. As the whole application of x-rays both for radiography and for treatment is bound up with the question of absorption of x-rays, the question of penetrating power will now be considered in detail.

It is first of all important to realize that the terms opacity, or opaqueness, or transparency, of a substance to x-rays are very indefinite. An experimental illustration will make the point clearer. Before the window of a charged electroscope of the kind shown in Fig. 123 is hung a sheet of aluminum several millimeters thick. On placing a small gas x-ray tube (operated by an induction coil developing some 10,000 or 20,000 volts) a short distance away, with its target pointing towards the window of the electroscope, it is found that the leaf of the electroscope remains stationary or falls extremely slowly. On using a larger tube, however, operated by an x-ray transformer on some 50,000 volts, the leaf falls in a matter of a few seconds. The aluminum is opaque to the first beam of x-rays, but far from it to the second. In other words, x-rays from some tubes are more penetrating than from others.

Again, the same bulb when operated under different conditions emits rays which have different penetrating effects. Suppose a hot filament tube is used, with always the same milliamperage, but at a series of different voltages. Suppose, further, that for each voltage the distance of the tube from the electroscope is adjusted so that in each case the leaf falls at the same rate, when no absorbing sheet of metal is present. If now another set of readings is taken from each voltage, at corresponding distances, with an absorbing layer of metal interposed, it is found that the higher the voltage the more rapidly the leaf falls. The conclusion is obvious—the higher the voltage across a tube the more penetrating are the rays emitted.

There are, therefore, different kinds of x-rays which we may describe as *hard*, *medium*, or *soft*, according as they are very penetrating, moderately penetrating, or feebly penetrating. It will be recalled (section 53) that the same terms are used to describe the state of a gas tube, a hard tube being one for which a higher voltage is required to maintain a certain current than for a soft one. But there is no confusion of terms, for we have just seen that a higher voltage across a tube means an increase in the penetrating power of the rays emitted. A hard tube, therefore, emits an excess of hard rays, a soft tube an excess of soft rays. But the terms *hard*, *medium*, and *soft*, are much too elastic for the accurate measurement of so important a quantity as the penetrating power and we must seek some means of expressing degrees of hardness by definite numbers. In other words, we need a scale in terms of which the *quality* of a beam of x-rays may be expressed.

**110 Quality and Tube Voltage** — Since the penetration increases with the potential difference across a tube, any device, such as a spark-gap meter or calibrated primary voltmeter, which measures the magnitude of this quantity, provides one means of estimating the penetrating power of the rays leaving the tube (See section 117) A number of years ago, the *Bauer Qualimeter*, an instrument for measuring quality, was on the market This was essentially an electrostatic voltmeter which indicated the tube voltage by means of a pointer moving over a scale marked with numbers reading up to 10 No 1 on this scale corresponded to a very low voltage and to rays which were completely absorbed by 0.1 mm of lead, and so on until No 10 indicated rays so penetrating that 1 mm of lead was required for their complete absorption Quality was then expressed in terms of these arbitrary numbers Such an instrument is not now used and it is mentioned solely to indicate an early attempt to establish a scale of quality

No matter how exact the device for measuring tube potentials this information in itself, important as it is, is not sufficient to describe accurately the quality of the beam of rays actually utilized This is true for several reasons (1) As we shall see presently, there is always a mixture of different kinds of rays leaving a target (2) Two tubes with exactly the same voltage, do not necessarily emit rays of exactly the same degrees of penetration (3) The hardness of what are called characteristic rays (to be discussed later) does not increase steadily with applied voltage (4) Layers of absorbing material are commonly placed between the tube and the place where the rays are desired and these *filters*, as they are called, alter the average quality of the rays More direct means of measuring quality are therefore desirable

In spite of the fact that a knowledge of the magnitude of the peak voltage across a tube does not give sufficient information to describe quality completely, in actual practice it is always desirable to give the value of this quantity In this connection L S Taylor gives the following rough classification of the quality of composite beams

Ultra soft (Grenz)	5 to 10 Kv
Soft (for diagnosis and superficial therapy)	20 to 120 Kv
Hard (for deep therapy)	120 to 250 Kv
Extra hard or super hard, greater than	250 Kv

**111 Quality and Half-Value-Layer (H V L)** — One of the most useful practical means of expressing the quality of a beam of x-rays consists in giving the *half value layer*, that is, the thickness of some standard substance, copper, for example, necessary to reduce the intensity of the beam by 50 per cent Obviously the more penetrating the beam, the greater the necessary



thickness. This method, it will be noticed, deals with the absorption of x-rays by matter, a very important question which, at this stage, we shall discuss only in its simpler aspects (See Chapter XII)

Suppose an electroscope  $E$ , Fig. 124 (or any other of the devices for measuring ionization to be considered later), is placed in the path of a beam of

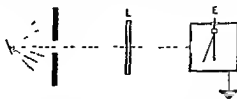


FIG. 124 A simple arrangement for examining absorption of a beam of x rays by an absorbing layer  $L$ .

x-rays, and that ionization readings are taken when successive increasing thicknesses of a material like copper are placed at  $L$  in the path of the rays. Results such as those given in Table XIII, an actual set taken by Dr. T. G. Stoddard, are obtained. These are plotted in graph 1, Fig. 125.

TABLE XIII — ABSORPTION OF AN X RAY BEAM BY COPPER

Thickness of Cu in mm	Intensity
0	100
0.25	63.3
0.5	48.1
0.75	39.3
1.0	30.45
1.25	26.9
1.50	23.0
1.75	20.6
2.00	18.3

From this graph, it can at once be seen that the thickness of copper necessary to reduce the intensity of the beam from 100 to 50 units, that is, a first 50 per cent is about 0.46 mm. If, however, we attempt to describe the quality of this beam by stating that the H.V.L. is 0.46 mm, we encounter a difficulty. The same graph shows that the additional thickness necessary to reduce the intensity a second 50 per cent, that is, from 50 to 25 units, is not 0.46 mm but more than 0.8 mm. Evidently the penetrating power of the rays which got through the first 0.46 mm of copper has increased. The conclusion is obvious — *the original beam must have contained a mixture of rays, some more penetrating than others.* The first absorbing layers, therefore, removed a

greater percentage of the softer, less penetrating rays, thus transmitting a beam with an excess of harder rays

It may well be asked What, then, is the use of describing quality by H V L if, when you work with a beam in the way we have just considered, you do

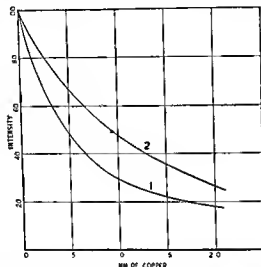


FIG 125 Absorption of a beam of x rays by increasing thicknesses of copper In Graph 1 intensity is plotted against thickness in Graph 2 the logarithm of the intensity

not always get the same result? The answer is that the H V L is not of much value nor generally used unless the beam of x-rays has been filtered *before* any absorption measurements are made, so that the softer components have been almost completely removed The H V L is then a good general

TABLE XIV — HALF VALUE LAYER

Kilovolts	Filtration 6 mm Cu	Filtration 15 mm Cu
400	5.1 mm Cu	5.7 mm Cu
500	5.4	5.8
550	5.8	6.1
600	6.1	6.4

guide to the average penetration of the remainder of the beam, although even then its exact value will depend on the amount of the original filtration The point is well illustrated by Table XIV, which gives some actual observations made by Bouwers and Van der Tuuk on the very penetrating rays leaving a tube operated on four different high voltages

Note two things (1) With the same filtration but increasing voltage, the rays are more and more penetrating, as shown by the steady increase in the H V L in either the second or the third column (2) After increased filtration, in this case 15 mm of copper as against 6 mm, the beam, for any particular voltage, is more penetrating In the third column, the magnitudes of the H V L are all consistently somewhat higher than those in the second, for the same voltage

Because of the wide range in the penetrating powers of different kinds of x-rays, the same substance is not suitable for expressing H V L over the whole range Soft rays for example, are so readily absorbed by copper that extremely thin sheets would be necessary in making the observations required to determine a H V L Aluminum is therefore often used as the standard substance for soft rays (20 to 120 Kv) and for the ultra soft region (5 to 20 Kv) celluloid may be used For hard rays (120 to 250 Kv) copper is the usual substance, while for the super-hard region tin has been suggested for 250 to 600 Kv, and lead above 600 Kv

When it is desired to have an intense beam of rays from a tube operated on low voltage, as in the Machlett tube described in section 71, or in some types of tubes used for diffraction studies, it is desirable to reduce the absorption by the walls of the tube itself For that reason windows made of some low-absorbing material, such as beryllium or lithium, are sometimes used The marked transparency of beryllium, for example, is shown by calculations made by T H Rogers on the total intensity of the radiation from a 50,000 volt Machlett tube transmitted by equal thicknesses of beryllium, aluminum and Pyrex glass His results show that, if the intensity of the beam transmitted by 1 mm of beryllium is taken as 100, the intensity after passage through 1 mm of Pyrex glass is only 8, and only 5 after passage through 1 mm of aluminum The element lithium is also remarkably transparent to low voltage x rays, a plate 1 mm thick absorbing a negligible amount When lithium is used as the window of an x ray tube, the outer side must be protected from the action of moisture in the air by a coat of grease or some other suitable material

**112 Homogeneous Beam and Exponential Law** — In Chapter XI we shall learn that it is possible to separate a beam of x rays into monochromatic components just as a beam of ordinary light is broken up into its constituent wave lengths When a *monochromatic* beam of x-rays is examined for absorption in the above manner, it is found that *no matter what the amount of the original filtration*, equal thicknesses of the absorbing material reduce the intensity of the beam by the same fraction, or, in other words that the

H V L remains constant whether the intensity is reduced from 100 to 50 units, or from 50 to 25, or from 25 to 12.5

Whenever the magnitude of any quantity changes according to such a law, that is, whenever, in the case of x-rays, for each successive equal thickness of absorbing material, the intensity decreases by the same fraction, the change follows the *exponential law*. Or, to take an example from radioactivity, whenever for each successive interval of time, the intensity of the rays from radium decreases by the same fraction, the change is exponential. As this law is of great importance in radiology, the student should try to understand it clearly.

TABLE XV — AN EXAMPLE ILLUSTRATING ABSORPTION OF A BEAM ACCORDING TO THE EXPONENTIAL LAW

Thickness of Absorber	Intensity	Logarithm of Intensity	Difference in Successive Logarithms
0	100	2.000	
0.25 mm	81.7	1.912	0.088
0.50	66.8	1.825	0.087
0.75	54.7	1.738	0.087
1.00	44.7	1.650	0.088
1.25	36.5	1.562	0.088
1.50	29.9	1.475	0.087
1.75	24.5	1.389	0.086
2.00	20.0	1.300	0.089

In Fig. 126 the curved line, which is a plot of the results given in the first two columns of Table XV, follows the exponential law, that is, it is applicable to the absorption of a pure homogeneous beam of x-rays by successive thicknesses of an absorbing material such as copper. Study it carefully and note the following three things:

(1) To reduce the intensity from 100 to 50 units, or from 50 to 25 requires the same thickness of copper, namely, about 0.86 mm.

(2) If we consider the increase in absorption brought about by the addition of the same thickness, for example, by 0.25 mm of copper, the reduction in intensity is always the same *fractional* amount, whether 0.5 mm is increased to 0.75, or 0.75 to 1.00, or 1.00 to 1.25, etc. Thus, reading off the graph we find that the first 0.25 mm reduces the intensity from 100 to 81.7 units or about 18 per cent, the second 0.25 mm, from 81.7 to 66.8, or again about 18 per cent, or the third 0.25 mm from 66.8 to 54.7, once more about 18 per cent.

(3) If the *logarithm of the intensity* is plotted instead of the actual intensity, the straight line shown in graph 2 of Fig. 126 is obtained. This indicates

that when absorption follows the exponential law, the log of the *intensity* decreases by equal amounts (not equal fractions) for equal changes in the thickness of the absorber. The same result is shown by the numbers in the fourth column of Table XV. If, then, we wish to test whether a curve is exponential or not, a simple way is to plot the log of the varying quantity, not the quantity itself. If a straight line is obtained, the law is exponential. By way of contrast note graph 2 of Fig 125. Although this is a plot of the log of the *intensity* of the beam against the thickness of absorber, graph 2 is not a straight line because the absorption of the beam, which is not homogeneous, did not follow the exponential law.

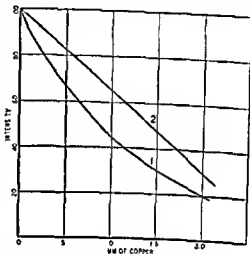


FIG 126 Graphs showing the absorption of a homogeneous beam of x rays. In Graph 1 intensity is plotted against thickness; in Graph 2 the logarithm of the intensity.

**113 Protection —** Before discussing in detail the most exact method of measuring the quality of a beam of x-rays (by analyzing it into constituent wave lengths), we may here conveniently make further reference to the question of protection. It will be recalled that, in section 64, certain facts were given about protecting an x ray tube so that, if possible, no rays leave the tube except in the direction in which they are wanted. But even if a tube is adequately protected in this way, protection must be provided from the direct beam itself. If sufficiently penetrating, this beam may easily pass through the walls of the tube room, causing injury to people in an adjoining room who may be completely unaware of its presence. In the diagnostic or treatment room itself, great care must be exercised by those actually using the beam. In screening, for example, where diagnosis is made by visual observation of the shadow picture on a fluorescent screen, the diagnostician, who is in the direct path of the rays, must be protected. This is accomplished to a considerable extent by covering the screen with transparent lead glass of sufficient thickness to absorb most of the rays which strike the screen.

Again, just as a beam of ordinary light is scattered by fine dust particles in the air, so a beam of x rays, on striking matter, may be scattered in all

directions and be radiated to places far removed from the direct path of the rays (See Chapter XII)

So important is the question of adequate protection that the International Congress of Radiology has drawn up certain recommendations. These are printed in an appendix at the end of this book. At this stage, we direct attention to the following

(1) Since in the beam which leaves a tube there is always a mixture of soft and hard rays, it is generally necessary to remove the softer components by filters. For example, suppose a deep-seated tumor is being treated by rays which, of necessity, must be fairly penetrating. If the soft rays were not removed by filtration, they would be absorbed by the skin and intervening tissue, with consequent danger of serious injury.

TABLE XVI—EQUIVALENT LEAD THICKNESS FOR ADEQUATE PROTECTION

Peak Voltage	Minimum Lead Equivalent
75 Kv	1.0 mm
100	1.5
125	2.0
150	2.5
175	3.0
200	4.0
250	6.0
300	9.0
350	12.0
400	15.0

(2) We have already emphasized that the higher the tube voltage, the greater the average penetration of the x-ray beam. So table protection against 50,000 volts rays will not then be adequate for 200,000 volts. Consequently protection rules specify the necessary minimum thickness of absorbing material, for a range of voltages. Because of its great density and availability, lead is more or less taken as a standard substance in specifying suitable thicknesses of absorbing material (see, however, section 134). Thus, in Table XVI, taken from the Recommendations of the British X-Ray and Radium Protection Committee, the numbers in the second column give the minimum equivalent thicknesses of lead for adequate protection against rays generated by the peak voltages in column one.

If lead itself is used, there are the actual thicknesses required. If, however, some other material is to be used, then by actual experiment, the equivalent lead thickness must be found. For example, in Table XVII and Table XVIII will be found equivalent lead thicknesses of iron and of concrete (2 parts

ballist, 2 parts sand, 1 part cement), as found by the National Physical Laboratory, England

Thus, when using x-rays generated at 200 Kv the equivalent of 4 mm of lead is obtained by 5.5 cm of iron or 27.5 cm of this kind of concrete.

TABLE VII — EQUIVALENT THICKNESSES OF LEAD FOR IRON

Lead Equivalent	Equivalent Thickness of Iron				
	150 Kv	200 Kv	300 Kv	400 Kv	radium gamma rays
1 mm	11 mm	12 mm	12 mm	11 mm	2.5
2	25	27	20	18	5
3	37	40	28	23	7
4	50	55	35	28	8.5

TABLE VIII — EQUIVALENT THICKNESSES OF LEAD FOR CONCRETE

Lead Equivalent	Equivalent Thickness of Concrete				
	150 Kv	200 Kv	300 Kv	400 Kv	radium gamma rays
1	85	80	60	50	8
2	160	150	95	75	16
3	230	210	125	100	22
4	295	275	150	120	29

It is interesting to note that at the highest voltages given in the tables, both iron and concrete, *relatively to lead*, become better absorbers

## PROBLEMS AND QUESTIONS

- 1 What effect has the speed of cathode rays on the nature of the x ray beam originating when the rays are stopped?
- 2 Describe a simple experiment to show that in general a beam of x rays consists of a mixture of hard and soft
- 3 Explain the purpose of an intensifying screen, as well as the principle underlying its use
- 4 Describe six properties of x rays
- 5 Describe two applications of the fluorescence excited by x rays in radiology
- 6 How would you test an x ray beam (without using a spectrometer method) to see whether it is homogeneous, or not?
- 7 A homogeneous beam of x rays has a penetrating power such that the half absorption value of aluminum is 2 mm. How much will the intensity of such a beam be reduced by 8 mm of aluminum? *Ans* 93.75 per cent

8 The intensity of a filtered beam of x rays is examined before and after passing through layers of aluminum 1, 2, and 3 mm thick and ionization values of 100, 80, 64, and 51.2 are obtained (a) Is this beam homogeneous and if so, why? (b) What is the HVL? *Ans* (a) yes, (b) 3.1 mm

9 Explain what is meant by HVL.

10 What is the general effect of a filter on a beam of x-rays?

11 Explain how the HVL of a beam of x-rays is altered when the tube voltage is increased

12 How is the quality of a beam of x rays as measured by the HVL method related to (1) the PD across the x ray tube, (2) the filtration used?



## CHAPTER XI

### MEASUREMENT OF WAVE LENGTH OF X-RAYS

**114 Reflection of X-Rays** — It has already been stated that the work of von Laue and his colleagues in 1912 proved without any doubt that x rays had a wave nature just like ordinary violet and ultraviolet light. Before that date other experimenters had tried with some success to prove the wave nature of x-rays. One of the simplest of the early experiments consisted in examining whether or not there was any spreading out when the rays fell on a narrow aperture. (See Fig 111) Although the results of experiments of this kind were not conclusive they did provide evidence that, if x rays had a wave nature, the wave lengths must be of the order of  $10^{-8}$  or  $10^{-9}$  cm. With this evidence in mind it occurred to von Laue that a crystal, whose regular structure was known to have a spacing between atom layers of the order of  $10^{-8}$  cm might act towards x-rays much the same as a diffraction grating acts towards light. The idea was tested by experiment and proved to be one of the most fertile in modern science.

In Laue's original experiment a narrow beam of x-rays traversed a zinc blende crystal, and the emergent beam fell on a photographic plate. On development the plate showed a regular pattern of bright spots on a dark background.

In interpreting this result W. L. Bragg of England showed that it was possible to look on cleavage planes of crystals as reflecting surfaces and, subsequently, in collaboration with his father, Sir William Bragg, developed a technique which proved of tremendous value for the analysis of an x ray beam as well as for the examination of structure of crystals.

Consider a narrow beam of x rays, represented by  $AC$  in Fig 127, incident on the face of a crystal in a direction making an angle  $\theta$  with this face. The question arises: Is there a reflected beam in the direction  $CD$ , as there is if  $AC$  represents a beam of light and the crystal face is replaced by a mirror? According to Bragg's ideas, which experiment soon verified many times over,

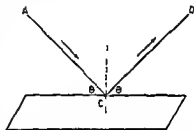


FIG 127 An x ray beam along  $AC$  under certain conditions is regularly reflected from the face of a crystal along  $CD$ .

a cleavage plane of a crystal with its very regular arrangement of atoms, acts as a mirror for x-rays, nature providing the smooth surface necessary to reflect regularly waves as short as those of x-rays. The reflection of x-rays from a crystal, however, differs in one important respect from optical reflection at a mirror. Since x-rays penetrate matter, there is a series of reflections from successive parallel planes of atoms. The beam  $CD$ , therefore, in reality consists of a number of superimposed beams, each reflected from a different plane of the crystal.

Now let us enlarge the scale of our diagram sufficiently to show successive layers, as we have done in Fig 128, for four layers. Then, remembering that

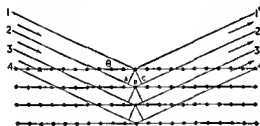


FIG 128 Reflection of x rays from successive parallel planes of atoms in a crystal

the planes are separated distances not much greater than  $10^{-8}$  cm, we see that even a narrow beam like  $AC$  when enlarged on the same scale, will, in Fig 128, be represented by several lines such as 1, 2, 3, 4, with corresponding reflected rays 1', 2', 3', 4'. Moreover, it is not difficult to see that the path of the disturbance along

$11'$  is shorter than that along  $22'$ ,  $22'$  shorter than  $33'$ , and so on. For disturbances  $11'$  and  $22'$  this path difference is equal to  $AB + BC$  as shown in Fig 128. With a little simple trigonometry, this can readily be shown to be equal to  $2d \sin \theta$ , where  $d$  is the distance between successive layers, and  $\theta$  is the angle which the beam of rays makes with the face of the crystal. For any successive pairs of disturbances, the path difference will be the same.

We see then, that the beam  $CD$  of Fig 127, really consists of a superposition of a number of beams, with a path difference between every successive pair equal to  $2d \sin \theta$ . Just as with a diffraction grating and ordinary light (see section 93), it follows that all the component beams will unite to form a resultant intense beam only if this path difference is equal to one, or two, or three or more wave lengths. This means that when a beam of homogeneous x-rays is incident on the face of a crystal, there is a reflected beam of marked intensity only for very special angles of incidence. If the incident beam contains a number of different wave lengths, then, for any given angle of incidence, there is an intense reflected beam only if there is a component whose wave length  $\lambda$  is such that  $\lambda = 2d \sin \theta$ , or  $2\lambda = 2d \sin \theta$ , etc. Analysis of a beam is possible, therefore, because each component is reflected in a direction different from any of the others. By rotation of a crystal to vary the angle

of incidence, it is then possible to spread out a beam of  $\lambda$  rays into first, second, third order spectra, just as in the case of the diffraction grating. Frequently we are concerned only with the first order, and in this book we shall confine our attention to that order.

**115 X-Ray Spectrometer** — A common arrangement for applying the above principle to the analysis of a beam of  $x$  rays is shown in Fig. 129. A narrow beam of  $\lambda$ -rays, after passing through the slits  $S_1$  and  $S_2$  cut in thick blocks of lead, is incident on the face of a crystal  $C$  set on the table of the spectrometer. By means of a scale rotations of the crystal through small angles may be measured accurately. A third slit  $S_3$  is so placed that any reflected beam which exists may enter an ionization chamber  $I$  placed immediately behind it. This slit must of course be placed so that the line  $OS_3$  makes the same angle with the face of the crystal as the incident beam. Since for each position of the crystal there is only a single correct position of the

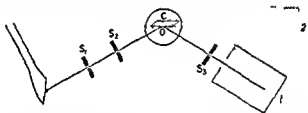


FIG. 129 Diagram showing the essential of an  $x$  ray spectrometer with ionization chamber

slit  $S_3$  and the ionization chamber, these are mounted on an arm by means of which they may be rotated about the central axis through  $O$ .

In actual use, the incident beam of rays to be analyzed is allowed to strike the face of the crystal at a number of different angles. For each angle, slit  $S_3$  and the ionization chamber are set in the correct position and the ionization current if any, measured. A graph is then made showing the way in which the ionization current varies with the angle of incidence. Alongside the axis on which the angles of incidence are plotted a wave length scale may be marked by using the fundamental relation  $\lambda = 2d \sin \theta$ , provided that a crystal with known  $d$  is used. Examples of such graphs are given in Fig. 131 and Fig. 132. These will be discussed presently.

**116 X-Ray Spectrograph** — The ionization chamber may be replaced by a photographic plate and a permanent record obtained of the  $\lambda$  ray spectrum. By way of illustration, reference is made to the *Seeman Spectrograph*, an instrument, especially designed for radiologists, which is small and compact and does

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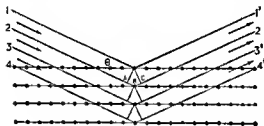


FIG 128 Reflection of x rays from successive parallel planes of atoms in a crystal

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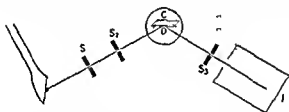


FIG 129 Diagram showing the essential of an x-ray spectrometer with ionization chamber

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not require as much experimental skill as the above spectrometer. The beam to be analyzed enters the instrument through a narrow slit  $S_1$ , Fig. 130, is incident on the face of a crystal immediately behind which a second narrow slit  $S_2$  allows any reflected beam which may be present to emerge and strike a

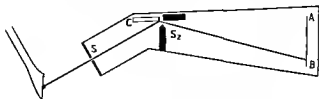


FIG 130 The Seeman x ray spectrometer

photographic plate in position  $AB$ . By means of a clock-work mechanism the portion of the instrument holding the crystal and the plate is kept in a regular oscillatory motion about the second slit as axis. In this way the original beam

strikes the crystal behind  $S_1$  at a series of different angles and regular reflection of each component takes place in the way we have already described. Wave lengths may be calculated by the use of  $2d \sin \theta$ , but actually the manufacturer of this instrument provides a scale by means of which wave lengths may be read off directly from the photographic plate.

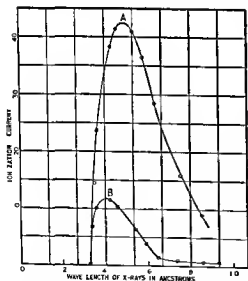


FIG 131 Graphs showing the analysis of a general beam of x rays by a spectrometer  $A$ , with out filter,  $B$ , with filter

**117 Shortest Wave Length** — The graph of Figs 131 and 132, made from observations by the late Dr Duane, a prominent x-ray worker at Harvard University, are typical of results obtained with the ionization chamber. The graphs show clearly two things (1) there is always a range of wave lengths in the beam leaving the target of a tube, and (2) there is a very critical minimum wave length at which radiation begins. Experiment shows that this shortest wave

length depends solely on the *maximum* voltage across the tube, and that these two quantities are connected by the following simple relation

$$\text{shortest wave length (in angstroms)} = \frac{12345^*}{\text{maximum voltage}}$$

For example, with 80,000 volts as peak value, the shortest wave length is about 0.15 angstrom. With 250,000 volts, the shortest is 0.049 angstrom. Although the shortest wave length is not the most intense (note again the graphs of Fig. 131), a knowledge of its value gives some indication of the quality of the beam.

If the shortest wave length can be read off a scale provided with such an instrument as the Seeman Spectrograph, the above relation provides us with an accurate method of measuring tube voltage. (See again, section 28.)

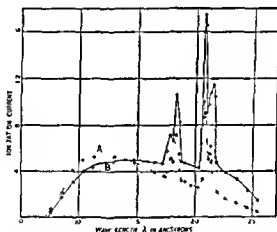


FIG. 132. Graphs showing the presence of characteristic x-rays, *A*, with filter 1 mm. of copper, *B*, with filter 12 mm. of aluminum.

**118 General and Characteristic Radiations** — An examination of Fig. 131 and Fig. 132 will show that the graphs differ in one important respect. In each of those in Fig. 131, the radiation covers a continuous range, beginning at the critical minimum wave length, then rapidly increasing to a region of maximum intensity, beyond which the intensity gradually decreases until the radiation ceases. In each of the graphs of Fig. 132, there

\* Although the number 12345 is a little in error, being more accurately written  $12.4 \times 10^3$ , the error in using the easily remembered 12345 is less than one per cent, an accuracy usually quite sufficient in radiology.

is an additional feature because isolated peaks of marked intensity occur at certain critical wave lengths

The same two types of x-ray radiation are shown photographically in Fig 133, in which each spectrogram corresponds to a different tube voltage. These photographs show clearly (a) the continuous radiation, beginning at

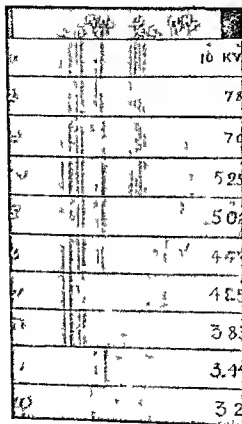


FIG 133 Spectrograms showing short wave length limits at different voltages as well as characteristic rays. In this figure wave lengths increase from right to left (Ross)

a critical wave length, whose magnitude varies with the applied voltage, and (b) the superposition, in all but the number 10, of isolated wave lengths

The difference between the two kinds of x ray spectra has an exact optical analogy. If the light from a white hot carbon of an arc lamp is examined with a spectroscope one observes a continuous spectrum with all colors ranging from red to violet. If the carbon arc is fed with a small quantity of a salt, barium for example one sees superimposed on the continuous spectrum isolated narrow spectral lines. Any white hot object will give a continuous spectrum but the number and the position of the isolated spectrum lines depends on the material put into the arc.

In the same way, an x ray tube with any metal as target, and operated on any voltage emits a continuous range of wave lengths whereas the values of the isolated wave lengths which

are sometimes although not always present, depend on the nature of the target. The continuous range is called the *general* or *white* or *independent* radiation, the isolated wave lengths, the *characteristic* radiation.

**119 White Radiation** — The total intensity of the beam of continuous rays depends on the following factors



(a) *The Current through the Tube* — Double the current, and the intensity is doubled, or, more generally, the intensity is directly proportional to the current

(b) *The Tube Voltage* — The intensity increases as the voltage across the tube increases. According to the work of Nicolas, the exact law is intensity varies as (voltage)<sup>3/2</sup>.

(c) *The Atomic Number of the Metal Used as a Target* — The higher the atomic number, the more intense is the beam

**120. Characteristic Rays** — Characteristic rays do not appear at all unless the tube voltage is sufficiently high. That is the reason none appear in the graphs of Fig 131, nor in spectrum 10 of Fig 133. With tungsten as target, potentials in the range 80,000 to 100,000 are necessary, and with uranium, characteristic rays are not emitted until nearly 115,000 volts are applied to the tube. The necessary voltage is proportional to the square of the atomic number. Thus, platinum, of atomic number 78, requires a voltage which is higher than that for tungsten, atomic number 74, by the factor

$$\frac{78 \times 78}{74 \times 74}.$$

It is well to note that, the higher the atomic number, the shorter the wave length of corresponding\* rays. This point is illustrated by the numbers given in Table XIX.

TABLE XIX — CORRESPONDING WAVE LENGTHS OF FOUR ELEMENTS

	Copper	Silver	Tungsten	Uranium
Wave Length	1.54	.56	.21	.15
Atomic Number	29	47	74	92

**121. Wave Length and Penetration** — Wave length measurements show that in radiology the range extends from about 1.0 to possibly 0.05 angstrom. By means of the spectrometer a beam may be separated into its constituent wave lengths and the absorption of each examined separately. The results of such investigations show that in general, the shorter the wave length, the more penetrating the beam. For example, using the numbers given in first and fourth columns of Table XX, we note that for  $\lambda = 0.064$ , the HVL in aluminum is 19.7 mm, for  $\lambda = 0.13$ , 13.7 mm, and for  $\lambda = 0.26$ , 6.35 mm. For the same three wave lengths, the HVL in copper are 3.9 mm, 1.36 mm, and 0.24 mm.

\* In section 124, the meaning of corresponding wave lengths is explained.

† See, however, section 134.

The numbers in Table XIX show that if feebly penetrating (very soft) characteristic rays are wanted targets made of metals of low atomic number should be used

TABLE XX—HALF VALUE LAYERS FOR A FEW WAVE LENGTHS

## Aluminum

$\lambda$	$\mu/\rho^*$	$\mu^*$	HVL
0.064	130	351	19.7 mm
0.098	156	421	16.4
13	186	502	13.7
175	228	616	11.2
2	270	729	9.5
26	402	1.685	6.35

## Copper

$\lambda$	$\mu/\rho^*$	$\mu^*$	HVL
0.064	198	1.76	3.9 mm
0.098	325	2.89	2.38
13	57	5.07	1.36
175	1.12	9.97	.69
2	1.59	14.15	.49
26	3.25	28.9	.24

\*The meaning of these symbols is explained in sections 136 and 137

**122 K, L, and M Rays** — An analysis of all the characteristic wave lengths emitted by a single element shows that they may be divided into groups. Table XXI, for example, gives the wave lengths in angstroms of three groups emitted by the element tungsten.

In accordance with certain theoretical ideas to be explained presently, the three groups are designated K, L, and M. A glance at the table will show that the wave lengths in the L and M groups are so long that ordinarily they are not used in radiology. Some of them are so soft that they are completely absorbed by the glass walls of a tube.

Individual lines in any group such as the K are often designated by Greek letters. For example, the most intense wave length in the K group of tungsten, 0.208 angstrom, is called the  $K_{\alpha_1}$  line, 0.213 is the  $K_{\alpha_2}$  line, 0.184, the  $K_{\beta_1}$ , 0.179 the  $K_{\beta_2}$ , and so on.

**123 Interpretation of K, L, and M Wave Lengths** — In order to give an explanation of the origin of characteristic wave lengths and their

arrangement in groups, it is necessary to simplify somewhat the picture of an atom given in section 36. It was there pointed out that an atom of atomic number  $Z$  consists of a nucleus with a positive charge of  $Z$  electronic units surrounded by  $Z$  electrons. The student's work in chemistry will have made him familiar with outer valency electrons one or more of which may be detached from the parent atom, leaving a positive ion. In the sodium family, for example, a single valency electron is the distinguishing mark

TABLE XVI—CHARACTERISTIC RAYS OF TUNGSTEN\*

K	L	M
213	148	898
209	147	894
185	128	856
184	124	734
179	109	697
		695
		693
		679
		674
		617
		607
		562
		534
		516

\*Values taken from *X Rays in Theory and Experiment* by Compton and Allison, D. Van Nostrand Company

which accounts for the similarity in the chemical properties of the members of this family. Normally, a sodium atom is a stable system, with the valency electron in equilibrium because it is revolving about the remainder of the atom in what we shall now call its innermost orbit.

Suppose, however, that we have a sodium salt in a flame which is emitting the yellow light characteristic of sodium. What now is the state of the atom and what is happening to cause the emission of characteristic sodium light? The main features of the answers to these questions were given in 1913 by the Danish physicist Bohr, who, at that time, was trying to interpret the characteristic spectrum of luminous hydrogen. According to Bohr's ideas an atom cannot emit radiation, which represents energy, unless previously it has had energy communicated to it. This, of course, is what is to be expected from the law of conservation of energy. If, by any means such as the impact of a moving electron, the outer valency electron is moved farther away from the nucleus than its normal position, work must be done against the force of attraction on the valency electron, and in consequence there is an increase in

the energy of the atomic system. If now the electron subsequently returns to its normal position, or part way to it, radiant energy is emitted in an amount equal to the loss arising from the return of the electron.

To explain the limited number of isolated characteristic wave lengths in the spectrum, Bohr assumed (1) that the valency electron could occupy only certain definite orbits, and (2) that for each transition from an outer to an inner orbit, a corresponding wave length is emitted. In Fig 134, for example, if the inner circle represents the normal stable orbit of the electron in the hydrogen atom, and the dotted circles the possible outer or *virtual* orbits, the lines with the arrow heads represent some of the possible transitions which give rise to corresponding emitted wave lengths. All this can be put in mathematical language and the results tested numerically, but in this book we shall consider only the quantitative aspect which connects wave length with the energy change.

For each electron transition or jump, a *quantum* or packet of radiant energy is emitted. The magnitude of a quantum is  $h\nu$ , where  $h$  is a definite quantity called Planck's constant in honor of the physicist who first introduced the conception of quanta, and  $\nu$  is the frequency of the emitted radiation. Since frequency =  $\frac{\text{velocity}}{\text{wave length}}$  or  $\nu = \frac{c}{\lambda}$ , where  $c$  is the velocity of all electromagnetic waves, we may write

$$h\nu = \frac{hc}{\lambda} = \text{energy change resulting from the electron jump, or}$$

$$\frac{1}{\lambda} = \frac{\text{energy change}}{hc}.$$

It follows that *the greater the energy change, the shorter the wave length emitted*. Referring again to Fig 134, we see that when an electron falls from orbit  $D$  to  $A$  the wave length emitted is shorter than for the fall  $C$  to  $A$ , a fall from  $D$  to  $B$  gives rise to a shorter wave length than from  $C$  to  $B$ , and so on.

The student should avoid giving too great a reality to this picture of an atom by thinking of these orbits as similar to circular grooves in which marbles run around a center. The orbital picture is extremely useful, especially to minds which find it necessary to visualize processes, but it must not be pushed too far. The pioneer work of Bohr has led to an interpretation of the origin of spectra which is more mathematical and much more difficult to visualize than the original work. But the basic relation connecting wave length with energy change remains of fundamental importance, and if the student will think of an orbit as a particular energy level, he will not go wrong.

In examining optical spectra, it is found that members of the same chemical family have features in common, and that an abrupt change takes place when we pass from one family in the periodic table to the next. In x-ray spectra, however, there is no such periodic change. We have already made reference to one example of this, when in section 120, it was pointed out that, as the atomic number of an element gets larger and larger, the wave lengths of corresponding x-rays steadily become shorter and shorter. The same point is illustrated by the fact that the  $K_{\alpha 1}$  wave length of all elements is represented to a fair degree of accuracy by the relation

$$\lambda = \frac{1170}{(Z-1)^2},$$

where  $Z$  is the atomic number of an element. This dependence of wave length on atomic number, a relation first revealed by the pioneer work of Mosely, suggests that the emission of characteristic x-rays is related, not to outer valency electrons, but to electrons which in heavy elements are very much nearer the nucleus.

To form some sort of picture of the origin of characteristic x-rays, we must examine a little more carefully the structure of atoms, particularly those of elements containing many electrons. A large number of experimental facts have led physicists to the view that the electrons are arranged around the nucleus at increasing distances, in groups or shells, as they are sometimes called, designated by the letters K, L, M, N, O, . . . , or by the numbers 1, 2, 3, 4, 5, . . . . Moreover, there is much evidence that the inner or K shell has 2 electrons, the L, 8 (subdivided into subshells), the M, 18 (subdivided into subshells), the N, 32, and so on. If, now, an atom is ionized by the removal of an electron from the innermost or K shell, much more work is necessary than that required to remove an electron from the L ring. This should be clear if it is realized that the electron in the K ring, being nearest the nucleus, is much more strongly attracted than when farther away, as in an L, or M, or N ring. Moreover, the repulsive forces arising from the surrounding electrons also make it more difficult to remove an electron from the K than from any of the outer shells.

In order to put an atom in the state where the emission of all of its characteristic x-rays is possible, first of all the atom must be ionized by the removal of an electron from the K shell. This may be done by electronic bombardment of a target, or, as we shall see in the next chapter, by absorption of a beam

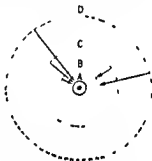


FIG. 134 When an electron falls from an outer to an inner orbit, energy is radiated.

of x rays of suitable wave length When an electron has been so removed, its place subsequently is filled by another electron coming in or "dropping" in from one of the surrounding shells If the drop is from the L shell, there is a certain energy gain and a characteristic ray of a definite wave length is emitted If the drop is from the M shell to the K shell, the energy gain is greater, and a shorter wave length is emitted For a drop from the N shell to the K shell, the emitted wave length is still shorter The K group of wave

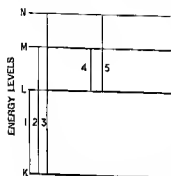


FIG 135 Schematic diagram to depict the emission of K x ray wave lengths by electron transitions to the K shell and of L wave lengths by transitions to the L shell

lengths, then, corresponds to electron drops or transitions from various outer shells or energy levels into the K level In Fig 135, 1, 2 and 3 represent three wave lengths in this group

If an electron has dropped from the L to the K level, the vacancy thus created in the L shell must be filled, and hence we have an L group of wave lengths corresponding to transitions from outer levels to the L level In Fig 135, 4 and 5 represent two such wave lengths Because of the smaller change in energy involved in transitions which end on the L level instead of the K, the corresponding wave lengths are longer (See again Table XXI)

In the same manner we may have an N group of still longer wave lengths corresponding to transitions of an electron from outer shells or levels to the N level

In Table XXI, it will be noted, especially for the M group, that more wave lengths are listed than might be expected from the above explanation This is due to the fact that the electrons in any one shell or level, such as the M, are arranged in subshells, and that, in consequence, the energy change when an electron goes from one subshell to the M level, to the K level, is slightly different from the change corresponding to a transition from another subshell of the M level to the K level

**124 Meaning of Corresponding Wave Lengths** — In section 120 reference was made to the fact that the greater the atomic number of an element, the shorter the wave length of a corresponding ray (See again Table XIX) By corresponding rays we mean those which arise from the same transition in energy levels Thus, for all elements, the wave lengths emitted when an electron drops from the L level to the K, or more exactly from the same sublevel of the L shell to the K, are corresponding The reason why the wave lengths of such rays get shorter as the atomic number  $Z$

lets larger, should now be evident. The greater  $Z$  the greater the positive charge on the nucleus, hence the greater the attraction of the nucleus for a  $K$  electron, hence the greater the work which must be done to remove a  $K$  electron out of its shell. When an electron returns to the  $K$  shell, there is therefore, a greater loss in energy, and a shorter wave length is emitted.

**125 Effective Wave Length** — In the above sections we have explained how a beam of  $x$  rays may be analyzed into its constituent wave lengths. Although such an analysis is the ideal way of describing the quality of a beam, the practical radiologist can scarcely be expected to examine quality in this way. He can, however, make use of wave length measurements obtained by other workers under laboratory conditions and by means of them record what is called the *effective wave length* of the beam he is utilizing. The meaning of effective wave length may be defined in several ways.

(1) In terms of H V L

Suppose an operator is provided with a table giving the H V L in copper for a series of monochromatic wave lengths such as we have given in Table XX. If, then, without any analysis into constituent wave lengths he determines the H V L for the beam he is using, he can read off from his table the wave length of the monochromatic beam which has this same H V L. That wave length would then be taken as the effective wave length of his beam.

(2) Through the absorption of a particular thickness of a standard substance

It is a simple matter to determine the percentage reduction in intensity of an unanalyzed beam brought about by, say,  $\frac{1}{2}$  mm. of copper. This requires only two readings with an instrument like an electroscope, one of the rate of fall before the introduction of the layer of copper, the other, after the copper is in place. (See Chapter XIII.) If, now, the operator is provided with a graph or a table giving the percentage absorption of  $\frac{1}{2}$  mm. of copper for a whole range of monochromatic wave lengths, he again can read off the value of that particular wave length which has the same percentage absorption as that of the beam he is using. This gives him his effective wave length.

Alternately, from the percentage absorption by the copper of the beam under examination, it is not difficult to calculate the absorption coefficient. (See section 136.) Then, from a formula connecting the coefficient with the wave length, the value of the monochromatic wave length which has the same coefficient can be calculated. This gives the effective wave length.

When this method is used, care must be exercised to specify the particular

thickness of standard absorbing material used, because somewhat different values of  $\lambda$  are obtained for each thickness. For example, in one investigation Dr Edith Quimby, of the Memorial Hospital, New York, showed that with a 1/10 mm of copper, 59% of a beam was transmitted, and  $\lambda$  was found to be 0.235 angstrom, with 0.47 mm of copper, 50% was transmitted, and  $\lambda$  was 0.208 angstrom, and with a layer of copper 1 mm thick, the transmission was 35%, and  $\lambda$  0.182 angstrom.

The reason for such differences in the value of the effective wave length of a mixed beam of x-rays is due to the fact that, in general, longer wave lengths are absorbed to a greater degree than shorter ones. As already pointed out in section 111, a beam containing a mixture of different kinds of rays becomes progressively harder, the greater the thickness of the absorbing material through which it passes. Hence, in methods (2) and (3), the copper used as an absorber actually alters the average penetration of the beam which is being

measured by an amount which is greater, the greater the thickness. It follows that the measured effective wave length should become shorter and shorter, the greater the thickness of the absorber. It also follows that the thinner the thickness of the copper used as a standard absorber, the more nearly the measured effective wave length represents that of the original beam.

(3) Through the ratio of equivalent thicknesses of two standard substances

The graphs of Fig 132 illustrate the important fact that the *relative* absorbing powers of two different substances vary with the wave length. From these graphs for example, we note that 1 mm of copper is a more

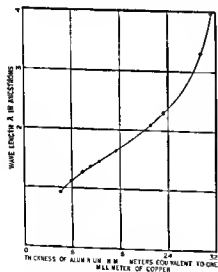


Fig 136 Standard graph (after Duane) for determining effective wave length

effective absorber than 12 mm of aluminum for wave lengths longer than 0.141 angstrom, but less effective for shorter wave lengths. Expressing this fact in another way we say that the particular thickness of aluminum which absorbs a beam of x-rays to the same extent as 1 mm of copper varies with the wave length. Such equivalent thicknesses of aluminum, as determined by Duane are plotted in Fig 136. By means of such a graph an operator can determine the effective wave length of a beam in still another way. All



that is necessary is to determine by actual experiment (1) how much the beam is reduced in intensity by 1 mm of copper, and (2) by using increasing thicknesses of absorbing layers of aluminum, the particular thickness which reduces the intensity of the beam by the same amount as the millimeter of copper. Suppose the equivalent thickness of aluminum was 16 mm. Then from this graph, we read off that, for a monochromatic wave length equal to 0.17 angstrom, 16 mm of aluminum absorbs to the same extent as 1 mm of copper. By this method, then, 0.17 angstrom is the effective wave length of the mixed beam.

**126 Relation of Focal Spot to Sharpness of Radiographs** — In earlier pages reference has been made to differences in the size of the focal spots on the targets of tubes. Before concluding, it is desirable to look at this question in the light of our knowledge that x-rays are short ether waves. Since this is the case, in radiography and fluoroscopy, the radiologist is dealing with shadow pictures, the details of which should be as clearly defined as possible. To obtain good detail, sharp shadows are necessary and these can only be obtained by having a small source of rays, that is, a fairly fine focal spot. The case is exactly analogous to the shadow patterns of obstacles placed in the path of light rays. A small source of light such as *P*, Fig. 62*a* (an uncovered arc lamp, for example), casts a sharp shadow of an object *O* on a screen. If, however, the source of light is comparable in size with the object, as shown in Fig. 62*b*, the portion of the shadow *AB* will be completely dark, whereas around it will be a region which receives light from some parts of the source, but which is cut off from other parts. The shadow is not sharp. In radiography it is exactly the same, and for good pictures it is necessary to have as fine a focus as the energy conditions will allow. However, care should be exercised that rays generated from parts of the tube other than the focal spot (as sometimes happens, since wherever electrons hit, x-rays originate) are not allowed to fall on the body to be examined.

On the other hand, in treatment, it is a question solely of the absorption of radiation and there is no need whatever to have a fine focus. Indeed, as in treatment a tube is generally operated continuously for some time, it is highly desirable that too fine a focal spot be not used.

## PROBLEMS AND QUESTIONS

1. Describe with diagram the spectrometer method of measuring in angstroms the constituent wave lengths in a beam of x-rays. Indicate on what two quantities the magnitude of the calculated wave length depends.

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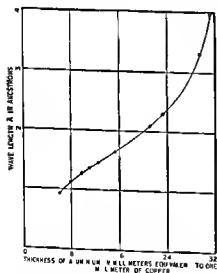


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## PROBLEMS AND QUESTIONS

1. Describe with diagram the spectrometer method of measuring in angstroms the constituent wave lengths in a beam of x-rays. Indicate on what two quantities the magnitude of the calculated wave length depends.

2 A beam of x rays, consisting of both general and characteristic rays, is analyzed with an ionization chamber and a spectrometer. Indicate the nature of the graph you would obtain. If a photographic method were used, what results would you obtain?

3 Explain why the Seeman spectrograph can be used as a voltmeter.

4 An x ray tube is operated on 150,000 volts. What is the shortest wave length emitted? *Ans* 0.082 angstrom

5 If the analysis of an x ray beam showed the shortest wave length to be 0.1 angstrom unit, what maximum voltage is applied to the tube?

6 Why can an x ray spectrometer be used as a high tension voltmeter? An x-ray tube is operated at a constant voltage. Draw a rough graph to illustrate the character of the rays emitted. If the voltage is equal to 200,000, what will the shortest wave length be?

7 What is meant by the effective wave length of an x-ray beam? Explain the fundamental principle involved in its determination by means of a Duane standard graph.

8 Show by a graph the distribution in intensity of x-rays with wave length when a tube is operated at constant potential. Indicate any differences that you might expect if the operating voltage were changed from say 50,000 volts to 200,000 volts.

9 In a few words, explain why, as a rule, L and M radiations are of no importance in radiology.

10 An x ray tube with a tungsten target is operated at P.D. of (i) 40,000 volts, (ii) 100,000 volts. In each case the beam of x rays is examined with a spectrometer and ionization chamber. If ionization is plotted against wave length, draw, very approximately, the type of curve obtained for each case, marking clearly the shortest wave length observed, and any outstanding difference between the two curves.

11 Radium C emits gamma rays of wave length 0.06 angstrom. What voltage would be necessary to obtain x rays of this wave length?

12 What is the general effect of a filter on a beam of x rays?

13 A betatron develops electrons possessing 100 mev. of energy. If the electrons are made to strike a target, estimate the shortest wave length of the resulting x rays.  
*Ans* 0.000123 angstrom

## CHAPTER XII

### SECONDARY X-RAYS AND ABSORPTION

**127. Secondary X-Rays** — In this chapter we discuss in detail what happens when a beam of x-rays is reduced in intensity by passage through an absorbing layer. Suppose we arrange an x-ray tube and an electroscope, as in Fig 137, so that no part of the *primary* beam leaving the target can enter the window of the electroscope. On operating the tube we find that the leaf falls very slowly. If, however, a block of wood, *R*, is placed in the path of the primary beam, the electroscope is discharged more quickly. This increased ionization is due to the emission by the wood of what are called *secondary* x-rays. The experiment illustrates the important principle that, whenever x rays fall on matter, there is a re-emission in all directions, of secondary x rays. This fact must never be forgotten. To stand out of the direct path of a beam of x-rays by no means insures protection from them, for we may be bathed in rays from objects against which the primary beam strikes.

Investigations regarding the nature of secondary x rays show that there are in general two kinds (1) *scattered rays*, which in general consist of two components, one whose wave length is the same as the primary beam, the other whose wave length

is longer, (2) *characteristic fluorescent rays* which are characteristic of the material of the radiator being in fact identical with the characteristic x-rays emitted by the same material when used as the target of an x-ray tube.

An optical analogy will perhaps help to make the difference between the two kinds clear. If a horizontal beam of red light is passed through a glass vessel containing water to which a few drops of milk have been added, the beam is quite visible when viewed from one side of the vessel. This is because of light *scattered* by the tiny particles, invisible in themselves, which

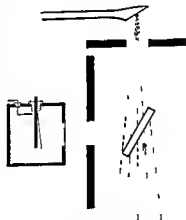


FIG 137 Experimental arrangement to show existence of secondary x rays

are in suspension in the water. If white light is used, the beam has a bluish cast when viewed from one side because the longer red and yellow wave lengths are scattered to a lesser degree than the shorter blues and violets. As we shall see in greater detail later, x-ray scattering arises from the impact of the original primary beam on electrons in the material through which the beam is passing. These electrons act as scattering centers, causing a re-emission of x-rays, not only at right angles to the original beam, but in all directions.

Again if certain substances are placed in the path of the beam from an arc light, or in direct sunlight, they are seen to fluoresce with a brilliant and characteristic color. Uranium glass, for example, emits a brilliant greenish light in this way, a solution of sulphate of quinine in sulphuric acid shows a characteristic and beautiful blue, and so on for many other substances. This fluorescent light is characteristic of the substance and is caused by the excitation of the primary beam of light falling on it. Characteristic fluorescent x-rays are closely analogous. They are characteristic of the substance and result from its stimulation by a primary beam.

**128 Scattered Radiation** — We note certain details of importance in radiology.

(1) Scattered rays are emitted in all directions (even backwards) by the radiator, but with a maximum intensity in the forward direction, that is, in the same direction as the primary beam. The shorter the wave length the greater the intensity scattered in the forward direction.

(2) *For elements of low atomic weight and a primary beam of short wave length, say not exceeding 0.25 angstrom, scattered radiation is of greater importance than characteristic.* Since tissue is made up almost entirely of the light elements hydrogen, carbon, oxygen, and nitrogen, this means that when a beam of short wave length traverses tissue, scattered rays are of very great importance. Further reference will be made to this question.

(3) When scattered rays were first studied, it was considered that their wave length was exactly the same as that of the primary beam. Further experiments, however, particularly those of J. A. Gray and A. H. Compton, show that the scattered beam consists of a mixture of *unmodified* rays, that is, those whose wave length is the same as that of the primary beam, and *modified* rays, those whose wave length is different. *For light elements and a primary beam of short wave length the intensity of the modified beam is relatively much greater than that of the unmodified, a fact which means that there is a progressive softening of a beam, or lengthening of wave length, when it traverses tissue.*

The magnitude of this change in wave length depends on the direction in which the scattered rays are being observed. If  $\phi$  is the angle the scattered beam under observation makes with the primary beam, Compton showed that  $\Delta\lambda$ , the change in wave length, is given by the relation

$$\Delta\lambda = 0.0243 (1 - \cos \phi) \text{ angstrom}$$

Thus, for  $\phi = 90^\circ$ , the change is 0.0243 angstrom, for  $\phi = 180^\circ$ , the change is 0.0486 angstrom. Hence, for a primary beam of wave length 0.2 angstrom, the scattered beam observed in a direction at right angles to the primary, has a wave length 0.2243 angstrom. If the primary beam is of very short wave length, 0.05 for example, the percentage change in the wave length of the scattered rays is considerable, this wave length being changed to 0.0743 at  $90^\circ$  and 0.0986 at  $180^\circ$ .

The reason for this change in wave length is given in section 132.

**129 Characteristic Radiation** — (1) As already noted, fluorescent characteristic rays are identical with the characteristic rays previously discussed (section 120), the difference between the two being solely in their mode of generation. Fluorescent rays result from the stimulus of an exciting primary beam of x-rays, not from the impact of electrons against a target.

(2) To excite fluorescent rays of the K group the wave length of the primary beam must be shorter than that of any of the characteristic rays in this group. Since the shortest wave length emitted by any of the first 35 elements in the periodic table is longer than 1 angstrom, and for elements with atomic numbers between 35 and 63 exceeds 0.3 angstrom, this condition is generally fulfilled for beams utilized in radiology, at any rate for all elements except those of high atomic weight. To excite the K characteristic rays of an element like tungsten, however, a primary wave length shorter than 0.18 is necessary, for platinum, shorter than 0.16, and for lead, shorter than 0.14 angstrom.

In this connection an important point relating to filtration arises. Suppose a primary beam contains a mixture of hard and of soft rays and that a filter of copper is used to remove the soft components. In traversing the copper, the hard primary rays will excite the characteristic rays of copper and hence these will emerge from the filter as well as a portion of the original hard beam. Now characteristic rays of copper are soft and may give rise to the injurious effect which the filter is put in to prevent. A second substance, aluminum for example, whose characteristic rays are still softer than copper, should then be used on the side of the copper remote from the tube. This substance will then absorb the soft secondary rays of copper, but its own

characteristic rays will do no harm because they are so much longer than those of copper that even a short thickness of air absorbs them

(3) *Relative to scattered radiation*, characteristic becomes more important for longer wave lengths In tissue, for example, to quote from Mayneord\* "for  $\lambda = 0.2$  angstrom, the absorption is 90 per cent scatter and 10 per cent fluorescent absorption, while at 1 angstrom, some 18 per cent only is due to scatter" Since the wave lengths utilized in deep therapy are often even shorter than 0.2 angstrom, we see again the importance of scattered radiation in therapy

For elements of high atomic weight, especially for longer wave lengths, absorption due to the excitation of characteristic rays is of greater importance than that due to scattered radiation

**130 Photoelectrons** — When the wave length of the primary beam is short enough to excite characteristic rays, there is a photoelectric emission of electrons by the radiator These electrons are of very great importance because part of the ionization caused by a beam of x-rays is due to them What happens is this A quantum of the incident primary radiation (if the wave length is short enough) has enough energy to eject an electron from the K shell of an atom of the radiator, or, alternately, a somewhat longer wave length may remove an electron from the L shell, or a still longer wave length, from the N shell In radiology, we are chiefly concerned with the removal from the K shell After the removal of the electron, characteristic rays are emitted in the way already described in section 123 When the incident quantum has more than enough energy to remove the electron, the excess energy goes into the kinetic energy of the electron In general, therefore, the ejected photoelectron has sufficient velocity to ionize atoms by collision This fact is of very great importance because it is the ionization produced in tissue which is responsible for any biological effects caused by x rays

If, however, the primary beam consists of extremely short wave lengths with corresponding quanta of high energy which are greatly in excess of the amount necessary to remove an electron, the chance of its removal is less than for longer wave lengths (See section 135)

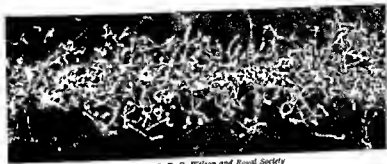
**131. Seeing Ions** — The ionization of a gas traversed by a beam of x-rays is very beautifully illustrated in Fig 138, an example of what is sometimes called a cloud expansion chamber or cloud track photograph As we

\* Mayneord, *The Physics of X Ray Therapy* p 41 (Churchill London)



shall have other occasions where we wish to visualize the presence of ions, the basic principles employed in taking a photograph like this should be understood. Although we cannot see an ion any more than an electron, it is possible by a very beautiful experiment, first performed by C T R Wilson at Cambridge University, to make each ion the center of a little drop of water which reveals its presence in unmistakable fashion.

The idea on which the experiment is based is really a very simple one. When air is laden with moisture, a fog will form much more readily if dust is present than if the air is dust-free. It has been said that if all the sooty



*Courtesy C T R Wilson and Royal Society*

FIG 138 A cloud track photograph showing paths of photoelectrons when a beam of x rays traverses a gas

smoke which pollutes the air over the city of London could be consumed or in some way prevented from leaving chimneys, fogs would be neither thicker nor more prevalent over that city than elsewhere in England. The suggestion is based on sound physics, because water condenses readily when little particles of dust or dirt are present to act as nuclei around which drops can form. Now Wilson showed that *ions also act as nuclei for the formation of water drops*. In the actual experimental arrangement ions are formed by an ionizing agent in moisture laden, but dust-free air, the air is allowed to expand suddenly, and thereby be cooled, water condenses on the ions, and a flash of light enables a photograph to be taken. *For each invisible ion, a visible drop appears*.

In Fig 138, then, each little white dot represents a droplet of water and hence an ion. The student should have no difficulty in tracing the irregular paths of some of the photoelectrons since they mark their trails by the ions they have formed.

Another method of revealing the track of an ionizing particle is described in section 168.

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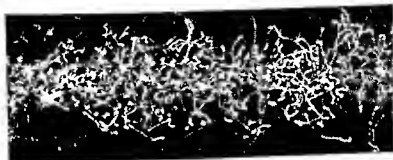
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**132 Recoil Electrons and Scattering.** — To obtain characteristic rays a photoelectron must be ejected from the atom. Scattered rays, on the other hand, arise from the impact of the primary beam against an electron which is comparatively free, that is, an electron not strongly held by the attraction of the nucleus of an atom. To explain the change in wave length which takes place on scattering, it is necessary to think of x-rays as having a corpuscular as well as a wave nature. Phenomena of interference have given ample evidence that ordinary light, x-rays, — in fact, all electromagnetic radiations, — have a wave nature. On the other hand, it is often necessary to interpret facts by thinking of radiation as concentrated in little bundles called *photons*, each photon possessing the quantum of energy, which we have seen in section 123, is equal to Planck's constant  $h$  multiplied by  $\nu$ , the frequency.

Now Compton showed that the observed change in wave length when a primary beam is scattered can be readily explained if we treat the impact of a photon against the scattering electron in much the same way as the collision of two particles. By applying the ordinary laws of conservation of energy and of momentum, he showed that if a photon with energy equal to  $h\nu$  strikes an electron (see Fig. 139), the photon goes off in direction  $\phi$  as scattered radiation with energy  $h\nu'$ , where  $\nu'$  is less than  $\nu$ , while, at the same time, the electron goes off in direction  $\theta$ , with initial energy equal to the difference between  $h\nu$  and  $h\nu'$ . This electron, usually called a *recoil* electron, may cause some ionization, although sometimes much less than that of a photoelectron. In some cloud-track photographs the ionizing paths due to recoil electrons may readily be observed.

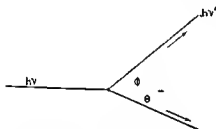


FIG. 139. An incident photon on striking a free electron is scattered in direction  $\phi$  as a photon of longer wave length and the electron goes off in direction  $\theta$ .

When a large number of scattering collisions take place, there are many different values of  $\phi$ , with corresponding values of  $\theta$ .

As shorter and shorter wave lengths are used, recoil electrons have more and more energy. Since, as we have noted in section 129, extremely short wave lengths cause comparatively little emission of photoelectrons (especially in materials of low atomic weight), it follows that for such wave lengths, the ionization in a medium like tissue is almost entirely due to recoil electrons. Stated otherwise, the ionization in tissue caused by x-rays generated by potential differences exceeding, say, 200,000 volts, is more and more due to

recoil than to photoelectrons, as the voltages get higher and higher. At potentials of the order of a few million volts, the phenomenon of pair production becomes important. This is discussed in section 206.

**133. Nature of Absorption.**—We are now in a position to examine a little more carefully the reason why an incident beam of x rays is reduced in intensity when passing through an absorbing layer. This reduction in intensity is due to one or more of the following causes:

(1) A *true* absorption, when some of the energy of the incident beam is expended in the production of photoelectrons. For each photoelectron liberated, one photon disappears, its quantum of energy being expended in removing the electron.

(2) An *apparent* absorption due to scattering. It is necessary to distinguish two types of scattering: (a) without emission of recoil electrons, (b) with associated emission of recoil electrons.

In case (a) the photons undergoing scattering are diverted out of their original paths *with no loss of energy*, and consequently with no change in wave length. The intensity of the original beam is reduced, therefore, not because any of the original energy is truly absorbed, but because most of the scattered photons are deflected out of the path of the primary beam.

In case (b), a photon which is scattered gives up part of its quantum of energy to a recoil electron and consequently is diverted out of the original path as a photon of less energy, or of longer wave length. Hence the portion of the energy of the original photon which is communicated to the electron is truly absorbed.

(3) *Pair Production*. This phenomenon, which can occur only when the energy of an incident photon exceeds 1.02 Mev, is discussed in section 206 and for the present need not concern us.

When absorption is dealt with quantitatively by the use of coefficients (see section 136), frequently a separate coefficient is used for each process. Thus, the symbol  $\tau$  is used as the photoelectric coefficient,  $\sigma$ , the scattering coefficient, subdivided into  $\sigma_s$  for true scattering,  $\sigma_a$  for absorption due to recoil electrons.

As will be evident from the preceding sections in this chapter, the relative importance of the various processes, and hence the numerical values of the coefficients, depend both on the nature of the absorbing material and the wave length of the primary beam of x-rays. For elements of low atomic weight, which are of special importance to the radiologist, and for short wave lengths or hard x rays, such as are developed by voltages exceeding say 200,000 volts,

photoelectric absorption is small or negligible. For long wave lengths or soft rays, generated by potential differences of 50,000 volts or less, photoelectric absorption is the more important for light elements.

TABLE XXII

Element	$\lambda$	Photons			Electrons	
		incident	emergent	scattered	photo	reco l*
Carbon	0.1	2000	1936	63	1	63
	0.7	2000	1740	80	180	50
Aluminum	0.1	2000	1917	74	9	74
	0.7	2000	491	105	1404	40
Copper	0.1	2000	1498	296	206	290
	0.7	2000	0	455	1545	15

\* The numbers in this column, especially those relating to  $\lambda = 0.7$  are very rough approximations estimated from data given on pp. 122 and 214 *X Rays in Theory and Experiment* Compton and Allison, D. Van Nostrand Company 1935.

The numbers given in Table XXII will give some idea of the relative importance of the various processes in the elements carbon, aluminum, and copper for the two wave lengths 0.1 angstrom and 0.7 angstrom. In obtaining these numbers a beam of x rays containing 2000 photons is assumed to be incident on 1 sq. cm. of a piece of absorbing material 1 mm. thick (actually the number of photons would be much greater than this) and, by the use of absorption coefficients a calculation is made of the number of photons emerging in the transmitted primary beam, the number deflected out of the beam by scattering, and the number absorbed in the production of photoelectrons. What is of importance is not the actual values of the various numbers but their relative values.

It should not be forgotten that a scattered photon may be re-scattered, with progressive lengthening of wave length, if recoil electrons are generated at each scattering; that in some cases a scattered photon of lengthened wave length may be completely absorbed liberating a photoelectron, that the photons associated with characteristic rays may also undergo scattering, the whole process especially in a large mass of tissue, being far from simple.

**134 Filtration and Critical Absorption Wave Length** — Reference has frequently been made to the use of filters for removing the softer components of a beam and it has been stated that, generally speaking, shorter wave lengths are more penetrating than longer. This statement we must now examine a little more carefully.

For a given absorbing substance, it is only partially true to state that the longer the wave length, the greater the absorption. When absorption measurements are made over a wide range of wave lengths, it is found that as the wave length is increased, at certain critical wave lengths, the absorption suddenly falls from a high to a low value. As a first illustration consider the element tin and the graph of Fig 140, which shows how the absorption for a fixed thickness of this element changes with changing wave length. On the horizontal axis of the graph, the wave length scale is in angstroms but the scale for absorption on the other axis gives only relative values. Starting with wave length shorter than 0.1 angstrom we note that at first tin is extremely transparent, but that gradually the absorption increases until the wave length 0.424 is reached. At this critical value, a sudden drop in the absorption takes

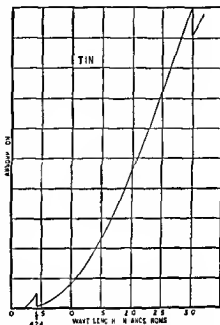


FIG 140 Graph showing change in absorption of tin with changing wave lengths

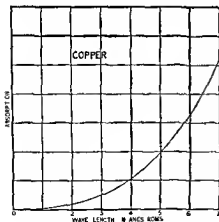


FIG 141 Graph showing change in absorption of copper with changing wave lengths

place, wave lengths just longer than 0.424 being transmitted much more readily than those just shorter. However, as the wave length continues to increase, the absorption again steadily increases until at approximately 3 angstroms, there is another sudden decrease. The qualifying word "approximately" is used, because actually there are three sudden changes, at 2.77, 2.97 and 3.15 angstroms.

The same general phenomenon occurs if tin is replaced by copper, except that the first sudden decrease in absorption does not take place until the wave length 1.38 angstrom is reached. In the graph Fig 141

the change in the absorption of copper for wave lengths as long as 0.7 angstrom is plotted. Contrast this graph with that of Fig. 142, which applies to lead. Note that for lead, the value of the first critical absorption wave length is 0.14

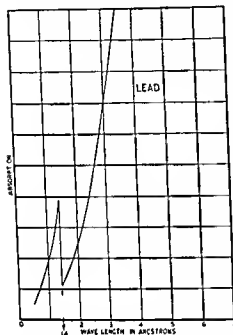


FIG. 142. Graph showing change in absorption of lead with changing wave lengths.

angstrom, a wave length right in the middle of the region used in deep therapy. It follows that a filter of lead is very undesirable, because of the high absorption of some of the very wave lengths which the operator wishes to use, that is, those just shorter than 0.14 angstrom.

In choosing a filter, therefore, care must be exercised that there is no critical absorption wave length in the region in which the wave lengths are wanted. A glance at the values of the shortest (or K) critical absorption wave lengths are given in Table XXIII, will show that, for the ordinary materials which may conveniently be used as filters, with the exception of lead (platinum and tungsten cannot be classed as ordinary materials), the critical absorption wave length is considerably longer

than the longest wave lengths usually used in radiology. For all these elements, if we restrict ourselves to radiology uses, the shorter the wave length, the more penetrating the beam.

**135 The Meaning of Critical Absorption Wave Lengths** — In section 120 we stated that in order to have an emission of characteristic fluorescent rays, the incident photon must have enough energy to remove an electron from the K or the L or the M shells. The energy of the photon is absorbed and used to do the work of removing the electron. We have also previously pointed out that the quantum of energy possessed by a photon has the magnitude  $h\nu$ , where  $h$  is Planck's constant and  $\nu$  is the frequency of the x-ray. Suppose now, we begin our absorbing experiments with an element like tin, using first a wave length as short as 0.05 angstrom. The corresponding frequency is then extremely high (since the shorter the wave length the higher the frequency), and the quantum of energy possessed by the photon



is far more than is necessary to remove a K electron. This photon is then not readily absorbed because we know from experiments dealing with energy exchanges of this kind that the probability of an absorption with consequent ejection of the electron is greater, the more nearly the energy possessed by the photon is equal to the energy needed to remove the electron. Now as the wave length of the primary beam is gradually increased, or the frequency decreased, the energy possessed by the photon becomes less and less until at a certain critical wave length, 0.424 for tin, it is exactly equal to the amount

TABLE XVIII — SHORTEST OR K CRITICAL ABSORPTION WAVE LENGTHS FOR A FEW COMMON ELEMENTS

Atomic Number	Element	Critical Wave Lengths
13	Aluminum	7.93 angstrom
26	Iron	1.74
28	Nickel	1.48
29	Copper	1.38
30	Zinc	1.28
47	Silver	0.485
50	Tin	0.424
74	Tungsten	0.178
78	Platinum	0.158
82	Lead	0.140

needed to remove the K electron. At that stage absorption becomes a maximum. For all wave lengths longer than this critical value, the photon has not enough energy to remove a K electron, and at first there is a marked decrease in absorption since the photons in this region have far more than enough energy to remove an L electron. But once more as the wave length increases, the absorption gradually increases again until it reaches a maximum at a second critical value, where the energy of the photon is exactly that required to remove the L electron. Because an electron can be removed from each of the L subshells, there are the three critical absorption L values to which reference has already been made.

It is interesting to note that, if we take the K critical absorption wave length, 0.424, and calculate the corresponding voltage by means of the relation

$$\text{maximum voltage} = \frac{12354}{\text{wave length in angstroms}}$$

the value we obtain, 29.1 Kv, is exactly equal to the voltage which must be applied across an x-ray tube with a tin target before the characteristic rays of this element are emitted. This agreement is due to the fact that, whether

we excite the complete x ray spectrum by the impact of electrons against a target, or by the absorption of a primary beam, the atom must be ionized by the removal of a K electron. In the latter case the energy utilized is that of the incident photon which, as we have already emphasized, depends on the wave length, in the former case, the energy is that acquired by an electron in falling through the potential difference across the tube. The two energies must be equal and that is the cause of the agreement between the values of the voltage calculated by means of the above relation and the experimental value found necessary to excite the characteristic rays. Indeed, it is not a difficult matter to derive the above relation connecting voltage and wave length, if we equate these two energies

If the student will refer back to page 47, he will be able to write down at once that the energy acquired by an electron after falling through  $V$  volts is equal to

$$V \times 1.6 \times 10^{-12} \text{ ergs} \quad (1)$$

Again, the energy possessed by a photon

$$\begin{aligned} &= h\nu \\ &= h \frac{c}{\lambda}, \quad \text{since frequency} = \frac{\text{velocity of waves}}{\text{wave length}}, \\ &= \frac{6.56 \times 10^{-27} \times 3 \times 10^{10}}{\lambda \text{ in centimeters}} \text{ ergs,} \\ &= \frac{19.68 \times 10^{-17}}{\lambda \text{ in angstroms} \times 10^8}, \\ &= \frac{19.68 \times 10^{-25}}{\lambda \text{ in angstroms}}. \end{aligned} \quad (2)$$

Equating (1) and (2), we have

$$V \times 1.6 \times 10^{-12} = \frac{19.68 \times 10^{-25}}{\lambda \text{ (in angstroms)}}$$

or

$$V \text{ (in volts)} = \frac{12300}{\lambda \text{ (in angstroms)}}.$$

(Using more accurate values, we obtain 12395)

\*  $h = 6.56 \times 10^{-27} \text{ ergs} \times \text{secs}$  the velocity of all electromagnetic waves  
 $= 3 \times 10^{10} \text{ cm per sec}$

**136. Absorption Coefficients \*** — In section 112, Chapter X, it was pointed out that when a homogeneous beam is reduced in intensity by passage through absorbing layers, equal thicknesses reduce the intensity by the same *fractional* amount, or, alternately, equal thicknesses reduce the logarithm of the intensity by equal amounts. When absorption is studied quantitatively, these ideas are utilized by adopting *absorption coefficients*.

The *linear absorption coefficient*, represented by  $\mu$ , is, by definition, equal to the reduction, per unit thickness, in the logarithm (to the base  $e$ ) of the intensity. Students who have studied logarithms will perhaps recall that the natural base, that is, the base which is used in the calculation of the actual numerical values found in log tables, is not 10, the common base, but the number  $e$ , which is equal to the sum of a series and to ten decimal places has the value 2.7182818284. According to our definition, then,

$$\mu = \frac{\log_e I_0 - \log_e I}{x}$$

where  $I_0$  is the original intensity and  $I$  the intensity after the beam has traversed a thickness equal to  $x$  cm. of the absorber.

To be of practical use, that is, in order that log tables may be used, we must change over to the base 10. When this is done, the factor 2.30 appears in the working formula

$$\mu = \frac{2.30 (\log_{10} I_0 - \log_{10} I)}{x}$$

A concrete example will illustrate the use of this relation. Suppose we wish to find  $\mu$ , for copper, for the particular wave length which is absorbed in accordance with the results given in Table XV, section 112. From this table we note that the intensity falls from an initial  $I_0 = 100$  units to  $I = 66.8$  units after the beam has traversed 0.50 mm. of copper. We have, then,

$$\begin{aligned} \mu &= \frac{2.30 (\log 100 - \log 66.8)}{0.05} \\ &= \frac{2.30 (2.0000 - 1.8248)}{0.05} \\ &= 8.06\dagger \end{aligned}$$

\* Sections 136 to 139 may be omitted in a first course.

† This expression may also be written  $I = I_0 e^{-\mu x}$ .

‡  $\mu$  can also be found using the exponential expression  $I = I_0 e^{-\mu x}$ . In this case  $66.8 = 100e^{-\mu \cdot 0.05}$  or  $e^{-0.05\mu} = \frac{66.8}{100} = 0.668$ . From exponential tables  $\mu$  can then be found

Again, using a thickness of 1 mm, with  $I_0 = 100$  and  $I = 44.7$ , we obtain

$$\begin{aligned}\mu &= \frac{2.30 (\log 100 - \log 44.7)}{0.1} \\ &= 8.04\end{aligned}$$

Or, taking one other example, since, when the thickness of absorber changes from 1.00 mm to 1.75 mm, the intensity drops from 44.7 units to 24.5 units,

$$\begin{aligned}\mu &= \frac{2.30 (\log 44.7 - \log 24.5)}{1.75 - 1.00} \\ &= 8.01\end{aligned}$$

The homogeneous beam of rays to which the results of Table XV apply, has, therefore, a linear absorption coefficient in copper of 8.0, and by this number its quality may be accurately described

**137 Mass Absorption Coefficient** — Of greater importance than  $\mu$ , is the *mass absorption coefficient*. Suppose we compare the absorption of a homogeneous beam by water in the liquid state with the same substance in the vapor state. If we keep the cross-section of our beam constant, we find that in order to obtain equal absorption by vapor and by liquid, such a thickness of vapor must be used that the total *mass* of water is the same as in the equivalent thickness of liquid. This suggests that a coefficient more fundamental than  $\mu$  is one in which we deal with *the reduction in intensity per unit mass, for a beam of unit cross section*.

$$\begin{aligned}\text{Now mass} &= \text{volume} \times \text{density} \\ &= \text{cross sectional area} \times \text{length} \times \text{density} \\ &= 1 \times x \times \rho\end{aligned}$$

for a beam of unit cross section, length  $x$  cm, and density  $\rho$  grams per cc. From our definition then we can write

$$\begin{aligned}\text{mass absorption coefficient} &= \frac{2.30 (\log I_0 - \log I)}{\text{total mass}} \\ &= \frac{2.30 (\log I_0 - \log I)}{x \times \rho} \\ &= \frac{\mu}{\rho}.\end{aligned}$$

For the radiation dealt with above, that is, the beam which has a linear absorption coefficient in copper of 8.0, the mass absorption coefficient, or  $\frac{\mu}{\rho} = \frac{8.0}{8.9}$  or 0.90, since the density of copper is 8.9 grams per cc.

In standard tables it is usually values of  $\frac{\mu}{\rho}$  which are given, for different substances and different wave lengths. For example, in an appendix to *X-Rays in Theory and Experiment* by Compton and Allison (D. Van Nostrand Co.), tables are given of the values of  $\frac{\mu}{\rho}$ , for all the elements, for a wide range of wave lengths. A few examples taken from that book are given in Table XXIV.

TABLE XXIV — VALUES OF  $\frac{\mu}{\rho}$  FOR ALUMINUM, CARBON AND COPPER

Wave length	0.4	0.72	0.98	1.30	1.75	2.00	2.60	4.17
Aluminum	130	143	156	186	228	270	402	118
Carbon	130	136	147	152	163	175	188	256
Copper	193	232	325	57	112	159	325	114

Using these results, we note that the wave length whose absorption was dealt with in Table XV, must have a value between 0.13 and 0.175 angstrom, since its  $\frac{\mu}{\rho}$  for copper is 0.90.

Note that for light elements such as carbon and aluminum, the values of  $\frac{\mu}{\rho}$  (1) are less than those of a heavier element such as copper, for correspond-

TABLE XXV —  $\frac{\mu}{\rho}$  FOR A FEW ELEMENTS FOR WAVE LENGTH 0.21 ANGSTROM

Material	$\frac{\mu}{\rho}$
Paraffin	0.21
Carbon	0.176
Aluminum	0.278
Copper	1.62
Lead	5.07

ing wave lengths, and (2) increase with increasing wave length much more slowly for light elements than for heavy. The first point is further emphasized by the values given in Table XXV (taken from Compton and Allison)

It follows from the second point that, if we confine ourselves to wave lengths within the range given in Table XXIV, copper is a much better material for a filter than the other two substances, because of the bigger contrast in the absorption of short and of long wave lengths

**138 A Numerical Example** — *Given a copper plate of thickness 2.2 mm, find how much it will reduce the intensity of a monochromatic beam of x rays of wave length 0.2 angstrom if  $\frac{\mu}{\rho}$  for this wave length is equal to 1.59*

$$\begin{aligned}\text{Since } \frac{\mu}{\rho} &= 1.59 \text{ and } \rho \text{ for copper} = 8.9 \text{ (gms per cc),} \\ \mu &= 1.59 \times 8.9 \\ &= 14.1\end{aligned}$$

Let  $I_0$  = the intensity of the beam incident on the copper plate,  
and  $I$  = the emergent intensity

$$\text{Then,} \quad \mu = 2.30 \frac{\log I_0 - \log I}{x}$$

$$\text{or} \quad 14.1 = 2.30 \frac{\log I_0 - \log I}{0.22}$$

$$\text{Therefore,} \quad \log I_0 - \log I = \frac{14.1 \times 0.22}{2.30} = 1.35$$

$$\text{or} \quad \log \frac{I_0}{I} = 1.35$$

Using log tables, we find that

$$\frac{I_0}{I} = 22, \text{ or } I = 0.045 I_0,$$

that is, the emergent intensity is only about 4.5 per cent of the incident

Using exponentials we have the following alternative solution

$$\mu = \frac{\log I_0 - \log I}{x}, \text{ can be written}$$

or, in this problem,

$$\begin{aligned}\frac{I}{I_0} &= e^{-1.4 \times 0.22} \\ &= e^{-0.308}\end{aligned}$$

From exponential tables, we find, as before, that  $I = 0.045I_0$

**139. The Coefficients  $\sigma$  and  $\tau$**  — As we have explained in section 131 of this chapter, absorption results from the two processes of scattering and photoelectric emission. The coefficient  $\mu$ , therefore, is frequently separated into a scattering coefficient  $\sigma$  and the true absorption coefficient  $\tau$ , or, if we use mass absorption coefficients, we can write

$$\frac{\mu}{\rho} = \frac{\sigma}{\rho} + \frac{\tau}{\rho}.$$

In refined measurements  $\sigma$  is separated into the component  $\sigma_s$  due to the apparent absorption by scattering, and the component  $\sigma_a$  due to the true absorption by recoil electrons.

For light elements  $\frac{\sigma}{\rho}$  changes slowly with increasing wave length, and the mean value of 0.2 in the deep therapy region gives a fair idea of its magnitude.

The value of  $\tau$  on the other hand, increases rapidly both with increase in wave length, and with increase in  $Z$ , the atomic number of the absorbing element, its magnitude being approximately proportional to  $\lambda^3 Z^4$ . Hence, for heavy elements and long wave lengths, values of  $\tau$  run into large numbers. Even for light elements, if we deal with wave lengths much longer than those encountered in deep therapy, the value of  $\tau$  is many times greater than  $\sigma$ . On the other hand, for extremely short wave lengths, the scattering coefficient becomes the more important because the small value of  $\lambda^3$  makes  $\tau$  small regardless of the value of  $Z$ .

If we deal with a sufficiently large range of wave lengths, because of the sudden changes in the absorption at the critical absorption wave length (section

135), we have corresponding sudden changes in both  $\frac{\mu}{\rho}$  and  $\frac{\tau}{\rho}$ . The graphs

of Figs. 140, 141, and 142 were plotted from values of  $\frac{\mu}{\rho}$  given in the tables in Compton and Allison's book.

It follows from the second point that, if we confine ourselves to wave lengths within the range given in Table XXIV, copper is a much better material for a filter than the other two substances, because of the bigger contrast in the absorption of short and of long wave lengths

**138 A Numerical Example** — Given a copper plate of thickness 2.2 mm, find how much it will reduce the intensity of a monochromatic beam of x-rays of wave length 0.2 angstrom, if  $\frac{\mu}{\rho}$  for this wave length is equal to 1.59

$$\begin{aligned}\text{Since } \frac{\mu}{\rho} &= 1.59 \text{ and } \rho \text{ for copper} = 8.9 \text{ (gms per c.c.)}, \\ \mu &= 1.59 \times 8.9 \\ &= 14.1\end{aligned}$$

Let  $I_0$  = the intensity of the beam incident on the copper plate,  
and  $I$  = the emergent intensity

$$\text{Then,} \quad \mu = 2.30 \frac{\log I_0 - \log I}{x}$$

$$\text{or} \quad 14.1 = 2.30 \frac{\log I_0 - \log I}{0.22}$$

$$\text{Therefore,} \quad \log I_0 - \log I = \frac{14.1 \times 0.22}{2.30} = 1.35$$

$$\text{or} \quad \log \frac{I_0}{I} = 1.35$$

Using log tables, we find that

$$\frac{I_0}{I} = 22, \text{ or } I = 0.045 I_0,$$

that is, the emergent intensity is only about 4.5 per cent of the incident

Using exponentials, we have the following alternative solution

$$\mu = \frac{\log I_0 - \log I}{x}, \text{ can be written}$$



or, in this problem,

$$\begin{aligned}\frac{I}{I_0} &= e^{-14 \times 0.22} \\ &= e^{-3.08}\end{aligned}$$

From exponential tables, we find, as before, that  $I = 0.045I_0$

**139 The Coefficients  $\sigma$  and  $\tau$**  — As we have explained in section 131 of this chapter, absorption results from the two processes of scattering and photoelectric emission. The coefficient  $\mu$ , therefore, is frequently separated into a scattering coefficient  $\sigma$  and the true absorption coefficient  $\tau$ , or, if we use mass absorption coefficients, we can write

$$\frac{\mu}{\rho} = \frac{\sigma}{\rho} + \frac{\tau}{\rho}$$

In refined measurements  $\sigma$  is separated into the component  $\sigma_s$  due to the apparent absorption by scattering, and the component  $\sigma_a$  due to the true absorption by recoil electrons.

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If we deal with a sufficiently large range of wave lengths, because of the sudden changes in the absorption at the critical absorption wave length (section 135), we have corresponding sudden changes in both  $\frac{\mu}{\rho}$  and  $\frac{\tau}{\rho}$ . The graphs of Figs. 140, 141, and 142 were plotted from values of  $\frac{\mu}{\rho}$  given in the tables in Compton and Allison's book.

**140 Scattered Rays and Radiography** — The aim of the radiographer is to obtain a shadow picture showing good contrast and definition

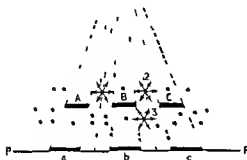
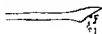


FIG 143 Shadows of objects *A*, *B*, and *C* are not sharp because of scattered rays from such sources as 1, 2 and 3

That scattered rays, in some cases, may lessen the sharpness of the picture to such an extent as to make it of little use should be evident from an inspection of Fig 143. In this illustration *a*, *b*, and *c* represent the shadows of three small obstacles, *A*, *B*, and *C*, on a photographic plate or film. If scattered rays were of no importance and the focal spot at *F* were fairly small, such shadows would ordinarily be sharp and the plate would show marked differences in density between the regions *a*, *b*, and *c* and their surroundings. Suppose, however, the objects *A*, *B*, and *C* are

surrounded by other particles of matter (as indicated by the small dots) which scatter x-rays in all directions. In that case sharp shadows would only be possible when the objects *A*, *B*, *C*



were placed near the plate or film, somewhat as illustrated in Fig 144.

If the objects are not near the film, sharp shadows will no longer be possible for two reasons. In the first place the scattered rays from each particle such as 1 and 2, Fig 143, will cast their own shadows and for each particle the shadow due to this cause will occupy a different position. Again scattered rays from many of the particles can pass under the objects and in this way affect the photographic plate in the region which the object shields from primary rays. For these reasons a good radiograph under such conditions would be impossible.

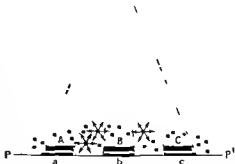


FIG 144 Shadows of objects *A*, *B*, and *C* are sharp if objects are close to the photographic plate

Now whenever an operator wishes to make a radiograph of a thick portion of the body he is up against this difficulty. Cer-

thin parts cannot be brought near the plate and scattering of x rays makes it impossible to obtain good results. Can the difficulty be overcome in any way?

There are two ways in which the desired improvement in contrast may be obtained, (1) by diaphragming, (2) by the use of the Potter-Bucky Diaphragm

### 141 Diaphragms and Secondary Rays

**Diaphragming** consists in limiting the aperture of the primary beam by means of an opaque filter with suitable opening. In Fig 145, for example, *AB* represents a diaphragm which limits the area of the beam on the plate to *MN*, whereas had a diaphragm been used of the size indicated by the dotted lines, the area would have been limited to *CD*. If now it is possible to diaphragm sufficiently

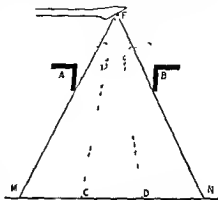


FIG 145 Effect of diaphragm on the cone of rays

when radiographing a thick body, considerable improvement in the contrast can be obtained. This may best be shown by giving some experimental results of Wilsey, of the Eastman Kodak Co., who made an extended study of the effects of scattered rays in radiography.

Wilsey by a simple experimental arrangement was able to compare the photographic intensity of the primary or focal beam with that of the scattered \*. Using an aperture which gave a picture on the plate 20 inches in diameter, and a layer of water 6 inches thick as the scattering material, he found the intensity of the scattered radiation to be 4.9 times that of the focal beam. By diaphragming until the picture was 8 inches in diameter scattered radiation was reduced to 4 times the focal, while if the picture were made 4 inches in diameter, the ratio was reduced to 2. In other words, if one could conveniently use a picture 4 inches in diameter, the effect of scattered rays is cut down considerably, but with a scattering layer 6 inches thick the effect of scattered rays is still twice that of the direct rays from the focal spot. While some improvement, therefore, is obtained by cutting down the aperture of the beam, the method is limited in its application and at best not very efficient.

**142 The Potter-Bucky Diaphragm** — In the Potter-Bucky diaphragm, the radiographer is supplied with an arrangement which very con-

\* Under 'scattered' is also included the radiation which might be present due to rays originating at places other than the focal spot.

siderably reduces the effect of scattered rays when thick portions of the body are being photographed. The underlying principle, as first suggested by Bucky, is simple. Suppose, as shown in Fig. 146, a grid of lead strips, separated by narrow slots, is placed between the object to be radiographed and the photographic plate. If the lead strips are placed so that they lie lengthwise along a curve somewhat as shown in the figure, it should be evident that if the target

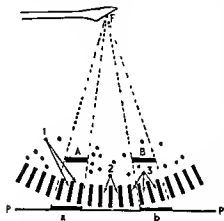


FIG. 146 Shadows of the objects *A* and *B* are cast only by rays travelling in the direction of the primary beam.

is so placed that the focal spot coincides with the intersection of the dotted lines in the figure, the only rays which can get through the slots and so strike the photo plate are those in the direction of the focal beam. Secondary rays in other directions are cut off by the lead strips, as is clearly shown in the figure in the case of a few rays from particles 1, 2, and 3. Sharp shadows of objects such as *A* and *B*, therefore, are cast. With a stationary grid of the kind described, however, such radiographs would be of little use, because the shadows of the lead strips themselves would be superimposed on the picture.

In the Potter-Bucky diaphragm this difficulty is overcome by adopting the simple device, suggested by Dr. Potter, of keeping the grid in steady motion throughout an exposure. By this means, since each portion of the plate is covered for the same length of time by each lead strip, the effect of grid shadows is eliminated. With such an arrangement excellent radiographs may be made of the thick portions of the body. The grid moves along a curved track and is thus always in the position to allow the passage of primary rays, while immediately above the grid a thin curved sheet of metal supports the patient.

**143. Causes of Grid Shadows.**—In using a Bucky diaphragm the time of exposure is increased considerably. This should be evident when it is remembered that under certain conditions the intensity of the scattered radiation may be as much as five times greater than that of the primary beam. If most of the scattered rays are removed by the grid, there is a consequent increase in exposure time.

To make the time of exposure very short, as is sometimes desirable, x-ray beams of high intensities must be used, that is, the tube current must be high.

Now when the Bucky diaphragm is used and the exposure is very short, sometimes shadows are observed on the photographic plate even if all the mechanical conditions such as tube position are satisfactory.

One cause of these shadows arises from a very high surge in voltage which may develop in some circuits when the primary circuit is closed at an instant when the alternating current is not at its zero value. Such surges, magnified by the high tension transformer, cause a momentary large tube current, and, therefore, a momentary extremely intense "flash" of x-rays, a beam which may be so intense as to throw a grid shadow on the plate. To prevent this type of grid shadow an arrangement, such as the Westinghouse Ignitron Timer, is used to insure contact of the primary switch being made at the right instant.

A second cause of grid shadows arises if the tube current is intermittent, as it is in ordinary self-rectifying units, or half wave, or full wave rectifiers (see



FIG 147 To illustrate synchronization of grid shadows *a*, *b*, *c* and *d*

again, Figs 78 and 85). With the types of current shown in these figures, there are really a series of "flashes" of beams of x-rays, each following the other (when the supply is 60 cycles per second) after an interval of  $\frac{1}{120}$  second for full-wave (Fig 85), or of  $\frac{1}{60}$  cycle, for self-rectified or half-wave arrangements (Fig 78).

Suppose an operator is taking a high speed photograph with a Bucky diaphragm. It might easily happen that the motion of the moving grid would synchronize with the flashes of the x-ray beam. This would happen if the speed of the grid were such that every  $\frac{1}{120}$  of a second, for full wave, or  $\frac{1}{60}$  of a second, for half-wave, the grid moved such a distance that the shadow of the strips came in exactly the same place each flash. In Fig 147 *a*, *b*, *c*, *d* represent four successive positions of the grid shadow pattern when there is this type of synchronization.

Such shadows could not possibly occur with constant potential x-ray equipment, because in that case there would be no intermittent flashes, but a nearly

steady tube current, as shown previously in Fig 89. At least one manufacturer has shown that even with a full-wave generator, it is possible to attach a unit, the Grid Line Eliminator of the Westinghouse, for example, which converts the pulsating potential into constant, "the capacitance of the Eliminator being such that during the exposure there is no moment when the x-ray intensity falls appreciably low." This unit is such that it may be readily switched in or out, that is, so that either constant or pulsating potential is available.

**144 Lysholm Grid** — Dr Lysholm has shown that it is possible to use a suitably constructed *stationary* grid. In this, absorption of scattered radiation is accomplished by exactly the same means as in the Bucky diaphragm. Although it is designed for fluoroscopic use, the manufacturer of the Lysholm grid states that it may be used with advantage in radiography because the faint shadow of the lead strips "by no means interferes with the diagnostic value of the radiograph." The grid is a light flat sheet which may conveniently be put into position and used to advantage by a radiologist whose outfit does not include a Potter-Bucky diaphragm.

### PROBLEMS AND QUESTIONS

- 1 Describe two ways of obtaining x rays characteristic of the matter from which they are emitted.
- 2 A very penetrating primary beam of x rays traverses a layer of matter containing both heavy and light elements and an observer with suitable apparatus examines all possible secondary emissions from the matter in a direction at right angles to the primary beam. State with brief explanations, what he observes.
- 3 Explain what scattered x rays are and discuss their importance in radiography.
- 4 Distinguish between scattered and characteristic fluorescent secondary x rays.
- 5 Describe an experiment to demonstrate the existence of secondary x rays.
- 6 Describe an experiment to enable you to find the relative intensities of the primary beam and of the secondary rays, at a given place in a medium traversed by a beam of x rays.
- 7 Discuss the importance of scattered rays in radiography and show how their harmful effects may be minimized by the use of a Potter Bucky Diaphragm.
- 8 Explain the construction of a Potter Bucky Diaphragm. State why it is used and under what conditions.
- 9 A beam of x rays traverses a layer of matter. Discuss what happens to the beam.
- 10 What is meant by the critical absorption wave length of an absorbing substance? Why is a knowledge of its value important in choosing a filter?
- 11 Explain why lead is not a suitable material to use as an x ray filter.
- 12 How does the penetration in copper of x rays of wave length  $0.15 \text{ \AA}$  compare with those of  $0.25 \text{ \AA}$ ?
- 13 What is meant by (a) a monochromatic beam of x rays, (b) characteristic x rays, (c) independent or general x rays?

14. A homogeneous radiation is reduced in intensity 50 per cent by a thickness of 0.5 mm of copper. (a) Plot a graph showing how the intensity falls off with increasing thickness of copper. (Note—Obtain 5 points in your graph, using copper thickness of 0.5, 1.5, 2.0, 2.5, and 3.0 mm.) (b) What is the name given to this type of graph? Give two examples of radiations whose absorption is governed by a graph of this kind. (c) Find the linear absorption coefficient for the above radiation. (d) If the density of copper is 8.9 gm per cc, find the mass absorption coefficient. (e) Find the emergent intensity for a layer of copper 2.6 mm thick. Ans (c) 1.38, (d) 0.155, (e) 2.8 per cent.

15. A parallel beam of x rays of wave length 0.080 Å enters an ionization chamber, and its intensity is found to be 100. (a) Find the intensities when 1 mm sheets of Al, Cu, and Pb are in turn interposed in the beam. The densities are 2.70, 8.93, and 11.37 gm per cc respectively, and the mass absorption coefficients are 0.143, 0.263, and 2.47, respectively. Ans 96.2, 79.1, 6.06. (b) Find the thickness of Al, Cu, and Pb which will reduce the intensity of the beam of wave length 0.080 Å to half value when interposed in turn. Ans 13.0, 2.93, 0.247 mm.

16. When an unfiltered beam of x rays is analyzed by an ionization spectrometer, indicate the general nature of the curve obtained (i) when characteristic rays are absent, (ii) when they are present.

17. If the HVL of a homogeneous beam of x rays is 2 mm Al, find by how much the intensity of the beam is reduced by 6 mm Al. Ans 37.5 per cent.

18. State two practical ways by means of which K wave lengths from tungsten can be emitted.

19. Name the two classes of secondary x-rays indicating briefly what connection, if any, exists between each and (i) photoelectrons, (ii) recoil electrons.

20. Explain the meaning and the origin of (i) photoelectrons, (ii) recoil electrons.

21. When there is a change in energy due to an electron transfer in an atom, how is the wave length related to the magnitude of the energy change?

22. Briefly list any similarities or differences between beta rays, photoelectrons, recoil electrons.

23. A homogeneous beam is reduced in intensity from 100 to 80 units by 1 mm of copper. Find the intensity after the beam has passed through 4 mm of copper.

24. A photon A on striking a material gives rise to a photoelectron; a photon B to a recoil electron. In each case, explain what happens to the original photon.

25. A homogeneous beam of x rays has a HVL of 0.5 mm Cu. Find what per cent is transmitted by 1.4 mm Cu. Ans 14.4 per cent.

## CHAPTER XIII

### MEASUREMENT OF DOSAGE FOR ROENTGEN RAYS

**145 Quality and Intensity** — In the field of radiology, x-rays are used in two general ways (1) in diagnosis, either by photography or by the use of the fluorescent screen, and (2) in therapy, where the aim is to bring about a beneficial effect on diseased tissue. In the latter field, where the rays are an agent for treatment, it is just as important to know the "dose" as it is in prescribing ordinary medicines. In either case, too large a quantity may kill instead of cure the patient. It is necessary, therefore, to consider somewhat in detail this whole question of dosage.

First of all, it will be evident that to describe accurately a given beam of x-rays two things must be known (1) its quality, and (2) its intensity at any particular place in the path of the beam. We have already explained how the quality is described by giving the constituent wave lengths of the beam, or its effective wave length, or the H V L in some standard material. So far, however, although some use has been made of the idea of intensity, the exact meaning of this term and its relation to dosage has not yet been discussed. The distinction between the two quantities, while simple, is so important that it is worth while noting in optical illustration. Suppose a red glass is held in the path of the beam of light emerging from a projection lantern and falling on a screen. If the light inside the lantern is made brighter (as can readily be done in the case of an electric arc by increasing the current), the red spot also becomes brighter. The light falling on the screen is still red, that is, its quality is unchanged, but its intensity has been increased.

Again in sound, a tuning fork may be struck very lightly so that it is difficult to hear the emitted note, or it may be struck violently and heard at a considerable distance. In both cases the quality of the emitted note is the same (unless harmonics are present), in the latter case, however, the intensity is greatly increased.

So in x-rays, we might operate a Coolidge tube always at constant voltage, but in one case with low milliamperage, in a second case, high. The effective wave lengths in the two cases would differ but little, in the second case, however, the intensity would be greater than in the former.



**146 Absolute Intensity and Law of Inverse Square** — From the focal spot on the face of the target of an x-ray tube, a beam of x-rays spreads out much the same as ordinary light rays from a small source of light. In each case energy is radiated from the source, and in each case the intensity of the beam at any point is measured fundamentally by the radiant energy which each second passes through unit area placed at right angles to the direction of the beam at this point.

In either case, if no energy is lost by absorption, it is not difficult to see that the intensity falls off with increasing distance according to the inverse square law. In Fig 148, all the energy which passes through the area  $ABCD$  also

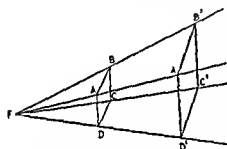


FIG 148 If  $FA' = 2FA$ , then the area  $A'B'C'D' = 4$  area  $ABCD$

passes through the area  $A'B'C'D'$ , since both x rays and light rays are propagated in straight lines. Now if the distance  $FA'$  is exactly twice  $FA$ , then the area  $A'B'C'D'$  is exactly four times the area  $ABCD$ .

Therefore the energy received per second per unit area at any point in  $A'B'C'D'$  is one quarter of the energy received per second per unit area at any point in  $ABCD$ . In other words if we double the distance,

the intensity falls to one quarter the value, or, in general, the intensity falls off inversely as the square of the distance from a small source, provided there is no absorption.

**147. Meaning of Intensity in X-Ray Dosage** — When x-rays are used for treatment, in general part of the x ray energy is absorbed, part is transmitted. Obviously the part which is transmitted plays no part in any beneficial or harmful effects the beam may have on tissue. The radiologist, therefore, is interested only in the portion of the beam which is absorbed by the tissue. He might, for example, have at his disposal two beams, one of strong intensity (measured fundamentally) and of extreme penetration, the other, of weak intensity and of feeble penetration. If each fell on the skin of a patient the second might have a greater biological effect than the first and if so, we might correctly say that as far as skin treatment is concerned its biological intensity was greater than that of the first beam.

In x ray dosage, we are interested in the absorbed energy only, and when we use the term intensity in radiology, we really are thinking of the absorbed energy per square centimeter per second. To distinguish this from funda-

mental or absolute intensity as defined above, the term *effective* intensity may be used, but, as this is not done in actual practice, we shall not do so. It must not be forgotten, however, that henceforth when we use the term intensity, we are thinking of its use in this restricted sense.

**148 Means of Measuring Absorbed X-Ray Energy** — The practical dosage problem in therapy, therefore, is to find in some way a means of stating that in a particular treatment so many units of x-ray energy were absorbed by tissue. At the outset it may be stated that there is at present no means of measuring directly the energy absorbed by tissue. We are forced to make use of the change which x rays on absorption bring about in some purely physical medium. For example, when x-rays fall on a strip of paper coated with a photographic emulsion, the rays which are absorbed cause a blackening of the paper after it is developed and the greater the amount of absorbed x-ray energy, the greater the blackening of the paper. Now if a beam of x-rays falls simultaneously on the skin of the human body and on a piece of photographic paper, the degree of blackening of the paper after development might be taken as a *measure* of the x-ray energy absorbed by superficial tissue during the time of treatment. As a matter of fact, in the pioneer days of dosage, such a method was used to some extent. It has one fatal objection — along with others — and that is, that the absorption of x-rays by the photographic emulsion does not change with changing wave length in the same way as absorption of tissue changes with changing wave length.

It is worth while briefly examining one or two other properties of x-rays which were utilized in the attempts to establish a satisfactory means of measuring dosage. In the *pastille* method, at one time used to a considerable extent by radiologists, the dose was measured in terms of the change in color in certain salts which results from the absorption of x-rays. A salt of barium platino-cyanide, for example, in the form of a round pastille some 8 mm. in diameter was exposed to the rays, the pastille being placed on a metallic sheet at a distance from the target equal to one half the distance to the patient. When in this position the absorption of a certain quantity of x-rays changed the color of the pastille from the original pale green to a brownish yellow, called Tint B. When rays were allowed to fall on the patient until this color change resulted, a unit dose as measured this way was delivered to the patient.

At the best this method could not be more than a rough guide. Moreover, neither this method nor that of the photographic strip gives any indication of the energy absorbed by tissue at some distance below the surface of the skin. The pastille method is also open to the same objection as was made to the use of the photographic strip. The absorption by the pastille

material with changing wave length does not parallel the corresponding change in absorption by tissue.

A somewhat more scientific method made use of the property which x-rays have of decreasing the electrical resistance of the element selenium. Although this method, as exemplified in the *Furstenau Intensimeter*, is open to similar objections, it is worth a brief examination if only for the sake of further illustrating some of the difficulties involved in the measurement of dosage. The experimental arrangement consists essentially of a selenium cell, *Se*, Fig. 149, placed in an electric circuit in series with a battery and a galvanometer. When no beam of x-rays is incident on the selenium the position of the pointer of the galvanometer is marked zero. If now a beam of rays falls on the cell, its resistance alters, the current increases, and the pointer takes up a new position at which it remains, provided the intensity of the beam does not alter. If the intensity of the beam is increased, a corresponding greater deflection is indicated. Hence the galvanometer scale may be marked in arbitrary units

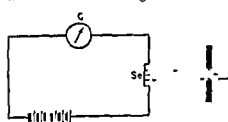


FIG. 149. To illustrate the use of a selenium cell in measuring x-ray intensities.

which are proportional to the intensity of the x-ray beam, or, more accurately, to the intensity absorbed by selenium.

Suppose it were found that when a certain beam, whose intensity was 2 units as measured by the scale of this instrument, fell on the skin of a patient for 30 minutes a mild erythema was produced. It would then be reasonable to state that, measured by this method, the particular dose required to cause such an erythema, is  $2 \times 30$  or 60 Furstenau units. If another time, a beam of the same quality were used but of intensity 4 units on this scale, it would be natural to assume that to produce the same biological effect, the rays would have to fall on the patient for only 15 minutes, since  $4 \times 15 = 60$  units as before. But the assumption that a weak intensity for a long time has the same effect as a strong for a correspondingly shorter time is not necessarily true, and has to be justified.

Again, if the quality of the beam of rays was now changed and its intensity adjusted until 2 units were again recorded by this intensimeter, it would be found that the time required to produce the erythema was no longer 30 minutes. A separate calibration would then be necessary for each kind of ray.

On the whole — and there are still other objections which need not be discussed — this method is not good enough for the exact measurement of dosage.

**149. Dosage by Ionization.** — The only property of  $\lambda$ -rays which can be used satisfactorily as a means of evaluating a physical dose having a direct relation to tissue dose, is the ability of a beam to ionize a gas like ordinary air. There are several reasons for this

(1) Over a wide range of wave lengths the ionization of air is directly proportional to the  $\lambda$ -ray energy absorbed

(2) Since tissue is largely composed of the light elements hydrogen, oxygen, carbon and nitrogen, what we might call the effective atomic weights of air and of tissue do not differ to any great extent. It is useful to remember that, over a wide range of wave lengths, the absorption per gram is nearly the same for air, for water, and for tissue

(3) Closely related to (2) is the fact that the absorption of air changes with changing wave length

in the same way as the absorption by tissue

(4) It is highly probable that the primary cause either of the beneficial or of the injurious effect of  $\lambda$ -rays on tissue is due to ionization

(5) The ionization method of measuring absorbed  $\lambda$ -ray energy lends itself to the establishment of a convenient, universal unit, which may readily be realized

It is necessary, therefore, to study in detail the whole question of ionization of air and its use in the measurement of x-ray dosage

**150 Saturation Ionization Current** — Consider the two arrangements illustrated in Fig 150 and in Fig. 151. In Fig 150, two plates,  $P$  and  $Q$ , separated by an air gap, are joined in series with

a battery  $B$  and a very sensitive galvanometer. In Fig 151, the plate  $Q$  is grounded and the insulated plate  $P$  is joined to the leaf of an electroscope. With the galvanometer arrangement there is normally no current because

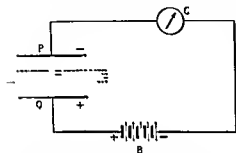


FIG 150 A very sensitive galvanometer  $G$  indicates a current when a beam of x rays ionizes the air between  $P$  and  $Q$

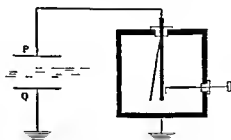


FIG 151 A charged electroscope attached to  $P$  is discharged when a beam of x rays ionizes the air between  $P$  and  $Q$

for moderate voltages air is a good insulator. With the electroscope arrangement, if the insulated plate and the leaf are given a charge, the leaf remains stationary for the same reason\*. Now suppose a beam of x-rays, indicated by the dotted lines in these figures, traverses part of the region between the plates *P* and *Q*. The air in its path is then ionized and, in the arrangement of Fig 150, the galvanometer (if sensitive enough) indicates a current or, in Fig 151, the leaf of the electroscope falls. A steady deflection is recorded by the galvanometer, because as long as the x ray beam is in action, there is a steady stream of ions, positive to the negative plate, negative to the positive. If the insulated system in the electroscope arrangement is positively charged, negative ions will go to *P* (positive to the earthed plate *Q*), and the leaf will drop at a rate which depends on the magnitude of the current of ions.

Should the beam of x-rays be made more intense, a greater number of ions is formed in each unit volume, a bigger ionic current flows, and a greater

deflection is recorded by the galvanometer, or, with the other arrangement, the leaf falls at a faster rate. Hence, either arrangement provides us with a convenient means of measuring the (absorbed) intensity of an x-ray beam, the first by the steady deflection of a galvanometer, the second by the rate of fall of the leaf of an electroscope. To make sure that the galvanometer deflection or the rate of

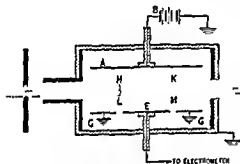


FIG 152 The essential features of a standard ionization chamber

fall of the leaf is *exactly* proportional to the absorbed intensity, an important condition must be fulfilled, and that is, the ionization current must have its saturation value. This means that the potential difference between the plates *P* and *Q* must be large enough to remove *all* the ions as fast as they are formed. If the voltage is too small some of the positive ions will unite with negative, or, to use the technical term, a certain number of positive and negative ions will *recombine*. The voltage, therefore, must be sufficiently high to prevent *recombination* so that as many ions reach the plates per second as are manufactured by the ionizing beam.

\* Actually due to defective insulation and to a *very slight* amount of ionization present at all times in the air the leaf falls very slowly, so slowly that often it can be neglected. In making exact observations it is an easy matter to correct for this *natural leak* as it is called.

In any of the arrangements we shall later describe, it is assumed that sufficient voltage is used to insure saturation

**151 Ionization Chambers** — In the arrangements used practically to measure ionization currents, the plates *P* and *Q* of Fig 150 and Fig 151 correspond to what is called an *ionization chamber*. We distinguish two main kinds (1) the *standard*, and (2) the small *thimble* chamber. The essential features of a standard chamber are shown in Fig 152. In this arrangement ions resulting from the passage of the beam of x-rays are driven from the volume *HKLM* to the collecting electrode *E* because of the electric field maintained between the plates *A* and *E* by the battery *B*, and the total charge coming to the electrode in any given time is measured by the instrument attached to *E*. Further details about the use of the standard chamber will be given presently. At this stage it is sufficient to state that it is not suitable for use by a practicing radiologist, but is used for standardization purposes.

The essential features of a simple arrangement with a thimble chamber are illustrated in Fig.

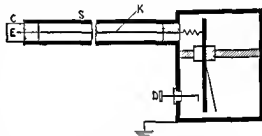


FIG 153 Arrangement for using a small ionization chamber *C* and an electroscope

153 *C* represents the chamber, which encloses a volume which may be of the order of one or two cubic centimeters. Its walls are of some light material — even paper will do — whose inner surface is made conducting by a thin coating of graphite and is grounded. *E*, the insulated electrode to which ions are attracted is joined to a measuring instrument, such as an electroscope or other type of electrometer, by the insulated conductor *K*. This conductor is shielded from electric disturbances by surrounding it with an outer earthed tube or shield *S*. To prevent ionization in the region between *K* and the outer tube, this space may be filled with an insulating material like rubber, or, by means of a vacuum pump, the pressure in this region may be kept so low that ionization by any radiation penetrating the shield may be neglected. If desired the tube connecting the electrode to the electrometer may be flexible and of any convenient length.

**152 The Roentgen** — Before discussing further details concerning ionization chambers, it is desirable at this stage to explain the nature of the fundamental unit in terms of which dosage is now measured.

Whatever arrangement used to measure an ionization current, it should

be evident that its magnitude depends on two factors, (1) the intensity of the beam, and (2) the volume of air from which the ions are removed. The greater the intensity, the greater the number of ions manufactured in each cubic centimeter, and, for a given intensity, the larger the volume from which the ions are collected, the greater the total number taking part in the current to the collecting electrode.

With these facts in mind, the student should be able to understand, at least in a general way, why in 1928 the Second International Congress of Radiology adopted the following definition of a physical unit, called the *roentgen*, in terms of which dosage can be measured.

*The roentgen is the quantity of x radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produces in 1 c.c. of atmospheric air at 0°C and 760 mm pressure, such a degree of conductivity that one electrostatic unit of charge is measured at saturation current.*

In 1937, at the Fifth International Congress, this definition was altered to the form given in section 153. Since for x rays generated by means of voltages as high as about 200,000, the two definitions agree in their practical application, we shall make use of the 1928 definition in our initial discussion.

It will be recalled that the electrostatic unit of charge (e.s.u.), which we have previously designated the statcoulomb (section 35), is such a quantity that when it is placed 1 centimeter away, in air, from an equal quantity, the force of repulsion of one on the other is 1 dyne. In actual calculations, it is more convenient to know that the coulomb, the practical unit of quantity, is related to the statcoulomb by the equation,

$$1 \text{ coulomb} = 3 \times 10^9 \text{ statcoulombs}$$

Suppose, in an arrangement like Fig. 152, a current of  $10^{-9}$  ampere is recorded by the measuring device and that the volume *HKLM* in which the ions are produced is 10 c.c.

$$\begin{aligned} \text{Since } 10^{-9} \text{ ampere} &= 10^{-9} \text{ coulomb per second,} \\ &= 10^{-9} \times 3 \times 10^9 \text{ statcoulombs per second,} \\ &= 3 \text{ statcoulombs per second,} \end{aligned}$$

we may write The number of statcoulombs produced in 10 c.c. in 1 sec = 3. Hence, the number produced per c.c. in 1 sec = 0.3. According to the above definition, the intensity of the beam producing the ions in the region *HKLM*, is 0.3r units per second. This assumes that the air is at 0°C and 76 cm pressure. For other temperatures and pressures the correction referred to in section 155 must be made.

It must be clearly understood that the roentgen is a unit of quantity, and that intensity has reference to the absorbed energy in unit time. If the above beam continued in operation for 10 minutes, the physical dose delivered in the region *HKLM* would be  $0.3 \times 10 \times 60$  or 180r units.

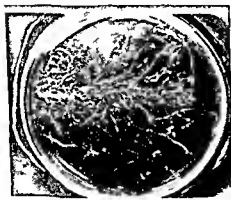
To fulfill the conditions expressed in the above definition of the roentgen certain precautions must be taken

(1) The current must have saturation value, (2) all the secondary electrons must be utilized, and (3) the wall effect of the chamber must be avoided. Let us examine each of these in turn.

(1) The meaning of saturation has already been explained and need not be further discussed.

(2) We have also previously explained that when a beam traverses a gas like air the ionization is due to the action of photoelectric and recoil electrons. Now these liberated electrons may travel outside the track of the primary

beam as shown by the cloud track photograph in Fig 138. For long wave lengths the "outside" effect is slight, but if the wave length of the primary beam is made shorter and shorter the excursion of the electrons out of the track becomes longer and longer. This means that ionization often takes place well outside the actual region traversed by the primary beam. This long excursion of the electrons is nicely shown in Fig 154, a reproduction of a photograph taken, with tube voltage 550 Kv, by Dr Walter Jordan at the California Institute of Technology and reproduced



Courtesy Charles C. Lauritsen

FIG 154 Passage of 550,000 volt x rays through a cloud chamber. Note the long excursion of the electrons.

through the kindness of Dr Charles C. Lauritsen. The tube voltage used when Fig 138 was taken is not available, but it is very much less than 550 Kv. If then all the ions are to be utilized — "the secondary electrons fully utilized" — the separation of the electrodes must be sufficient to insure that none of these electrons strike containing walls before they have used up their energy in ionizing. The actual separation depends on the kind of rays used, being greater the shorter the wave length. For x-rays generated by voltages up to 180,000 or 200,000 volts, a spacing of 12 cm is sufficient, but for x rays generated by a million volts the range of secondary electrons is so much greater that the overall dimensions of the standard chamber must be greatly increased.



In this connection the student may well ask "If ions are formed outside the region *HKLM* (Fig 152), is it correct to use only the volume of *HKLM* in making calculations?" In considering the answer to that question the student must distinguish carefully between (a) the *conversion process*, whereby part of the energy of an x-ray beam is truly absorbed, being converted into the kinetic energy of photoelectrons and/or recoil electrons, and (b) the subsequent process in which these secondary electrons gradually lose their energy by creating ions along their paths. Obviously, in a standard chamber, the conversion process takes place in the region *HKLM*, although for x-rays of very short wave length many of the ions formed by the ejected electrons are outside this region (See Fig 154). Although the 1928 definition of the roentgen does not state the fact explicitly, the cubic centimeter in that definition does refer to the region *HKLM* where the electrons are liberated by the primary beam, that is, where the energy conversion process takes place. In this respect the 1937 definition discussed in the next section is more exact.

(3) If x-rays are allowed to strike the walls of the chamber, secondary x-rays and electrons may be emitted, and these may add to the ionization of the air between the electrodes. In an actual standard chamber, therefore, the primary beam is carefully isolated by protecting diaphragms, with the electrodes well separated as noted above. As a still further precaution, the walls of the chamber are made of materials of low atomic weight so that if any stray radiation did strike them, the emitted fluorescent rays would be so soft (see section 120) that they would be absorbed before having produced any appreciable ionization.

**153 1937 Definition of the Roentgen** — At the Fifth International Congress of Radiology held at Chicago in 1937, a somewhat different definition of the roentgen was provisionally adopted in order to make this unit available for gamma rays of radium and for the ultrahigh voltage x-rays now in use (See Chapter XV). The new definition reads as follows:

*The roentgen shall be the quantity of x- or gamma-radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 e.s.u. of quantity of electricity of either sign.*

In many respects the two definitions are identical, and no change need be made in the work of the preceding pages. Note, however, the following:

(1) 0.001293 grams is the mass of 1 cc of air at 0°C and 760 mm pressure.

(2) Saturation conditions are not mentioned because the definition refers to the number of ions produced per cubic centimeter by the radiation and naturally includes all of them. In making measurements, however, it is just

as necessary as ever to use sufficient voltage to insure that the ions do not recombine

(3) The ions to be considered are those produced by the corpuscular emission per 0.001293 grams that is by the secondary electrons (photoelectric and recoil) set in motion by the primary beam. This corresponds to the clause in the 1928 definition requiring the utilization of all the secondary electrons, *but*, as already noted *specifies without any ambiguity* that the volume to be used in calculating the number of  $r$  units is the volume of the region in which the primary beam produces its "associated corpuscular emission"

**154 Determination of Effective Volume** — In considering the exact value of the volume  $HKLM$  to be used in calculating the number of  $r$  units two factors are of importance. The first has to do with the nature

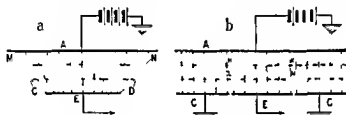


FIG. 155 By the use of guard plates  $G$  and  $G$  a uniform electric field can be maintained between  $A$  and  $E$  as in  $b$ . In  $a$  the field is far from uniform.

of the electric field between the charged plate  $A$ , Fig. 152 and the collecting electrode  $E$ . Since charged particles move along electric lines of force, the ions in an arrangement like that shown in Fig. 155a, move to  $E$  out of the region  $MNCD$ . The volume of this region varies with the relative size of the plates and is not easy to measure. For accurate calculation, the lines of force should run as nearly perpendicular as possible over the whole face of the electrode  $E$  somewhat as shown in Fig. 155b. This is accomplished by surrounding this electrode with the grounded guard plates  $G$  and  $G$ . If initially  $E$  is also grounded as is usually done in standard measurements (see section 155) and if the gap between  $E$  and the plates  $GG$  is narrow, then the ions are drawn to  $E$  from the volume  $HKLM$  whose length is equal to the distance from the center of the narrow opening on one side of the electrode to the center of the other opening.

The second factor relates to the cross sectional area of the beam of primary rays. This is controlled by the use of diaphragms which narrow down the primary beam and enable an exact calculation of the cross sectional area to be

made. As standard chambers are used only in standardization laboratories further details are omitted in this book.

By examining Fig. 156 the student should see readily several things: (1) ions will go to the electrode  $CD$  from the whole region  $ABCD$ , (2) electrons which originate in the region  $HKLM$ , but most of whose ionizing paths (such as 1 and 2) are outside the volume  $ABCD$ , will create many ions which do not go to the collecting electrode, and (3) other electrons (such as 3 and 4), which did not originate in the region  $HKLM$ , will create ions within the

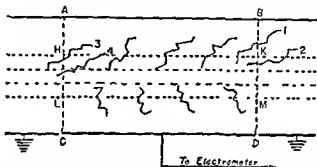


FIG. 156. Lines 1 and 2 represent tracks of electrons produced in the region  $HKLM$ , lines 3 and 4, tracks of electrons produced outside this region.

volume  $ABCD$  which do go to the electrode. There is therefore a loss of ionization from electrons which have moved out of  $ABCD$  and a gain from other electrons which have moved into this region. In standard ionization chambers designed for highly penetrating rays which give rise to secondary electrons with long paths, the loss can be made equal to the gain by making sure that the dimensions of the chamber are sufficiently large that electrons move into the volume  $ABCD$  from distances equal to the maximum forward range of those which move out.

**155. Null Method of Measuring Ionization Current.** — It has been stated in the preceding section that a suitable electric field is obtained in a standard chamber when both the guard plates  $GC$ , Fig. 155*b*, and the electrode  $E$ , are at ground potential. In actual use  $E$  is initially grounded, but this connection to earth must be broken before any measurement can be made of the charge carried to  $E$  by the ions, in any time interval. If this charge were measured by direct connection to an electrometer, the potential would steadily change as time went on, and in consequence the electric field would also change sufficiently to introduce an appreciable error in the calculated volume. To overcome such an error, in laboratories such as the Bureau of Standards in

Washington, and the National Physical Laboratory, Teddington, a null method is used. Figure 157 illustrates in simple form the arrangement used in one such method. It will be seen, is connected both to the measuring electrometer and to one side of a standard condenser  $C$  whose capacity is accurately known. The other side of the condenser is connected to a source of potential whose magnitude may be varied, the polarity being so chosen that

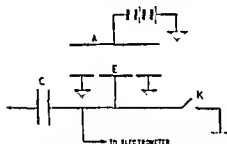


FIG. 157 By varying the voltage across the condenser  $C$  the ion charge coming to  $F$  may be annulled, thus keeping  $F$  at the original ground potential.

the charge on the side of the condenser connected with  $F$  is opposite in sign to the charge on the ions coming up to  $F$ . When a measurement is being made, initially the key  $K$  is closed, thus grounding  $F$  and the system to which it is attached. With the x-ray beam in operation,  $K$  is then opened, and a stream of ions begins to flow to  $F$ . But, as  $F$  accumulates a charge, the potential applied to the condenser is steadily altered in such a way that an equal charge of opposite

sign is induced on the side of the condenser connected with  $F$ . The resultant charge on the system joined to the electrometer is therefore kept at zero, and the indicator of the electrometer remains unchanged in position.

To determine the total charge  $Q$  coming to the electrode in an observed time  $t$ , all that is necessary is to calculate the magnitude of the charge given to the condenser. A numerical example will illustrate the method.

The intensity of a beam of x-rays at a certain place was measured by a standard ionization chamber arranged so that the effective volume in which ions were produced was 2.51 c.c. When the collecting electrode was attached to a condenser of capacity  $127 \times 10^{-6}$  microfarad, it was found that the electrometer remained undeflected if at the end of 1 minute the potential applied to the condenser was changed by 9.2 volts. Calculate the intensity in r units per minute. (The volume refers to air at  $0^\circ\text{C}$  and 760 mm pressure.)

$$\begin{aligned} Q &= \text{compensating quantity on condenser} \\ &= \text{capacity} \times \text{potential} \\ &= 127 \times 10^{-6} \times 10^{-6} \times 9.2 \text{ coulombs*} \\ &= 127 \times 10^{-12} \times 9.2 \times 3 \times 10^9 \text{ statcoulombs} \\ &= 3.505 \text{ statcoulombs} \end{aligned}$$

\* 1 microfarad =  $10^{-6}$  farad. An alternate method of calculating the number of coulombs is to use the relations 300 volts = 1 statvolt and 1 microfarad = 900,000 statfarads.

Therefore, the number of statcoulombs collected in 1 minute, if the volume were 1 c.c.

$$= \frac{3\ 505}{2\ 51} = 1\ 4,$$

or, the intensity of the beam

$$= 1\ 4r \text{ units per minute}$$

**156 Correction for Temperature and Pressure** — When measurements are made with a standard chamber, the air is not in general either at  $0^{\circ}\text{C}$  or 760 mm pressure. A correction must therefore be made for these factors. Since the absorption of  $x$  rays is directly proportional to mass, all that is necessary is to reduce the observed volume at  $t^{\circ}\text{C}$  and  $P$  mm pressure to its value under standard conditions. By application of the elementary gas laws, we can write at once

$$V' \text{ c.c. at } t^{\circ}\text{C and } P \text{ mm pressure} \\ = V \times \frac{273}{273 + t} \times \frac{P}{760} \text{ c.c. at } 0^{\circ}\text{C, and 760 mm}$$

In any problems given in this text, we shall assume that this volume correction has been made.

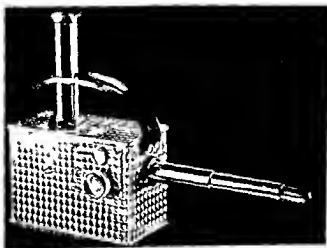
**157. Thimble Chambers** — Because of its fundamental importance, detailed attention has been given to the explanation of the means of measuring in  $r$  units per second the intensity of a beam of  $x$  rays by the standard chamber. In actual practice, the radiologist or his technician makes use of the thimble type of chamber rather than a standard because by such means in a very short time he can evaluate the dose in  $r$  units or the intensity in  $r$  units per second. It should never be forgotten, however, that previously someone had to calibrate his thimble chamber with the aid of a standard.

We must now amplify the information about small ionization chambers given in section 151. To begin with, it is well to note that except in rare cases the ionization produced per cubic centimeter in a small chamber is not the same as that produced per cubic centimeter by the same beam at the same place, in free air. There are several reasons for this. (1) Because of absorption of the primary beam by the walls of the chamber, the ionization is reduced. This effect can be lessened by using chamber walls of extreme thinness but (2) whatever the thickness, secondary electrons emitted by the wall material increase the ionization. (3) The corpuscular electrons produced within a small volume strike the walls before they have exhausted their ability to ionize.

generated by say 100 to 200 kilovolts, the wall thickness suitable for an air-wall chamber is a fraction of a millimeter. "For million volt x rays, 2 mm walls are necessary, for the gamma rays from naturally radioactive materials the required thickness is about 4 mm" (Quimby)

For very soft x-rays in the low voltage group, the absorption by even thin-walled chambers becomes sufficiently great to throw out the balance, and hence such a chamber suitably calibrated for 100 to 200 kilovolt rays cannot be used without correction. Around 45 kilovolts, the matter is further complicated with chambers whose walls are carbon coated because of the photoelectrons emitted by this element with such rays.

**158. Victoreen Condenser-Meter.**—This type of instrument, a photograph of which is reproduced in Fig 158, consists of two main parts (1) a narrow cylindrical piece, *E* to *B*, Fig 159, which at one end has an



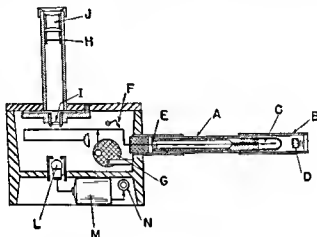
*Courtesy Victoreen Instrument Company*

FIG 158 Photograph of the Victoreen Condenser Meter

ionization chamber *C*, and (2) a box housing a fibre electrometer (electroscope), a device for giving an electric charge to the electrometer, and a lamp *L* to illuminate the fibre. On top of the box a low power microscope *J* to *I* enables an observer to view the image of the fibre against a scale. The central electrode of the ionization chamber passes through solid insulating material such as amber, and on emergence at the end *E* of the cylinder next the box makes electric contact with the fibre of the electrometer. It will

be noted that the main body of the cylinder is essentially a condenser, consisting of the central conductor, the dielectric surrounding it, and the outer earthed wall

In use, the insulated system, fibre plus connecting conductor and central electrode, is given such a charge that the image of the fibre, which is deflected an amount proportional to the potential to which it is charged, comes to rest on the zero of the scale. The cylindrical tube, which is attached to the box by a kind of bayonet socket, is then detached, and the cap *B* protecting the



*Courtesy Victoreen Instrument Company*

FIG 159 Diagram showing details of the Victoreen Condenser *r* Meter

ionization chamber is removed and placed over the opposite end *E* of the tube thus protecting the exposed end of the central conductor. The tube is then held with the ionization chamber in the path of the x ray beam at the place where the intensity is to be measured, for a measured time interval, which is frequently 1 minute. Because of the resulting ionization in the chamber a part of the charge on the collecting electrode and attached condenser unit is neutralized. At the end of the minute the cylinder is taken out of the x ray beam, the protecting cap replaced over the chamber, and the tube inserted into the box so that electrical connection is once more made with the electrometer. Because of the loss of charge, the potential of the electrometer drops a certain amount and the fibre, or its image, moves from the original zero to another part of the scale. Because of previous calibration the numbers on the scale read roentgens directly. Thus, if 15 were now read on the scale, the intensity of the beam at the spot where the chamber had been placed, would be 15 *r* units per minute.

By using different types of tubes and chambers condenser meters of various ranges are available. For example, the Victoreen Instrument Company advertises meters reading up to 25r, 100r, and 250r units per minute, as well as a very sensitive one for measuring stray radiation reading only to 0.25r per minute. This firm states that with a single chamber, "measurement is possible for any wave length radiation from that produced by a standard x-ray tube at 60 Kv P up to and including gamma rays of radium, with a wave length error not exceeding 6 per cent at both extremes. A calibration curve can be supplied giving the necessary correction if any, within 2 per cent."

Other chambers involving more or less the same fundamental principles, are available, which record the *total dose* in r units during the progress of a treatment. In the Victoreen Integrator, for example, the progress of a dose up to 300r units may be watched by means of a pointer moving over an ordinary scale. In the Hammer Dosimeter, the electrical arrangement is such that every time a collecting electrode has acquired a charge equivalent to a dose of 5r units, a clock mechanism moves the hand of a dial one division, while at the same time the electrode is discharged and made ready to collect another charge.

**159 Air Dose, Tissue Dose, and Back Scatter** — In the preceding sections we have shown how the intensity of a beam may be measured at a specified place *in air* by an ionization chamber. In therapy, the radiologist is interested primarily in the dose delivered to *tissue*, and that question we must now examine. Since it is reasonable to assume that the action of x-rays in therapy is due to the resulting ionization in tissue, and since to a first approximation ionization in tissue is the same as in an equal mass of air, tissue dosage is measured in terms of the ionization caused in a small cavity of air situated, if possible, in the midst of the region under treatment. In superficial treatment, a small ionization chamber can be placed on the skin of the patient, and the skin dose measured directly. In deep therapy, it is as a rule impossible to imbed the chamber in the tissue and the depth dose has to be found by experiments with a *phantom*, that is, a medium which is the equivalent of tissue in its absorption and scattering.

The magnitude of the skin dose is not the same as that measured at the same spot with the patient removed. At this stage the student will not be surprised at that statement, but it is so important that a reference to a simple experiment is not amiss. Suppose that at a certain place in air an operator has found that the intensity of an x-ray beam is 2r units per minute, and that he repeats his measurement with his ionization chamber resting on the skin of a patient, but without any other change. He finds that the second measure-



ment indicates a greater intensity than  $2r$  per minute. The reason for the increase has already been given in Chapter XII. The primary beam gives rise to scattered rays in the tissue of the patient, and many of these — the *back scatter* — are scattered back into the ionization chamber, thus increasing the ionization. The correct skin dose must include back scatter.

Many measurements of skin dose have been made by the method given in the preceding paragraph, that is, with the ionization chamber on the skin of the patient, but the results have shown that different types of chambers do

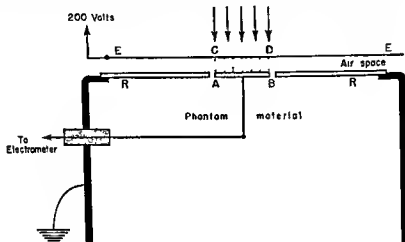


FIG 160 To illustrate the basic principle of the Failla extrapolation ionization chamber (Adapted from illustrations by Failla and Quimby)

not always agree. Recently a very careful study of back scatter has been made by the radiological department of the Memorial Hospital, New York, under the direction of Mrs Edith Quimby. It is worth while noting one or two features of a special ionization chamber utilized by Dr Quimby in this study. The chamber, designed by Dr Failla, of the Memorial Hospital, is a standard instrument, that is one by means of which the dose in roentgens can be calculated from measurements of the ionization current and of the volume in which ions are produced. The essential features are shown in Fig 160 which has been adapted from published illustrations by Dr Failla and Dr Quimby. Note the following:

- (1) The x-ray beam passes vertically, not horizontally (as in the standard chamber of Fig 152), *through* an upper electrode *EE*.
- (2) This electrode, which is maintained at a potential of say 200 volts, consists of organic material like very fine net silk, or parchment, or presswood, made conducting by India ink or Aquadag.

(3) The lower electrode  $AB$ , to which ions go from the volume  $ABCD$ , and the surrounding guard ring  $RR$ , are parts of the same piece of material, the Lucite, whose upper surface has been made conducting by India ink, except for a narrow insulating ring around  $AB$ . The lower side of this hole piece, electrode and outer ring, is in contact with scattering material such as presswood or a mixture of rice and flour which acts as a phantom or human tissue.

(4) By means of micrometer screws, not shown in the figure, the upper electrode can be raised or lowered, so that readings may be taken for different thicknesses of the thin layer of air separating the upper and lower electrodes.

Because of this feature, the instrument was originally called an *Extrapolation Chamber*. The idea was to measure the ionization per cubic centimeter in thinner and thinner air layers, as well as for upper electrodes of different

TABLE XXVI — SKIN DOSE CORRESPONDING TO 100 ROENTGENS IN AIR

Quality HVL in Copper	Area of Field in Sq. Cm			
	5	25	100	400
0.035 mm	110	117	124	128
0.3	114	124	134	147
1.0	114	124	136	149
2.0	109	117	126	136

thicknesses, and finally to extrapolate to find the ionization per c.c. for a negligibly thin layer in contact with the phantom, that is to evaluate a true measure of the skin dose. Actually it was found that for x-rays generated by 100 to 200 kilovolts, there was no change in the ionization per c.c. for air layers ranging from 0.5 to 3 mm. and no difference between upper electrodes made of extremely thin silk and of parchment.

With such a chamber, the most careful measurements of surface dose were made and tables drawn up giving the correct skin dose corresponding to a specified number of roentgens in air, for a wide variety of conditions. A few actual numerical values, taken from the published work of Dr. Mumby, are given in Table XXVI.

The numbers in the table show that the skin dose equivalent to 100r units in air varies with (1) the quality of the primary beam, and (2) the area of the field. For example, if we use always the same area, say 25 sq. cm., the skin dose is 117 units for the softest rays, 124 for the next two more penetrating rays, but falls again to 117 for the most penetrating beam. This variation is due to change in scattering with changing quality.

On the other hand, if we use always rays of the same quality, those with

an H V L equal to 1.0 mm. of copper, for example, we see that the equivalent skin dose steadily increases with increasing area, changing from 114 units for the smallest area to 149 for the largest. The increase with increasing field is due to the increased importance of scattered radiation. The larger the area, the greater the volume from which rays are scattered back to the chamber or to the area of skin under treatment. In Fig. 145, if the diaphragm limiting the width of the beam to *CD* is widened increasing its width to *MN*, scattered rays come to a small chamber placed over *CD* from a much greater volume than with the smaller opening, and hence a greater ionization is recorded.

For the same reason, if a thin portion of the body, such as a hand, is treated superficially, the back scatter is less for the same field, than for an area backed by a thicker portion of the body. In Table XXVI the numbers are based on the assumption that there is enough underlying material to give maximum back scatter.

**160. Depth Dosage.**—In therapy, the problem is generally that of treating diseased tissue below the skin. There are then two important problems (1) how to effect a cure without injuring the skin and the healthy intervening tissue, and (2) how to measure correctly the *depth* dose delivered to the diseased tissue. We shall consider the second problem first.

TABLE XXVII — NUMBERS OF ROENTGENS DELIVERED AT VARIOUS DEPTHS, FOR 100 ROENTGENS IN AIR QUALITY OF RAYS GIVEN BY H V L 1.0 MM IN COPPER

	5 sq cm		25 sq cm		100 sq cm		400 sq cm	
Depth	50 cm	70 cm	50 cm	70 cm	50 cm	70 cm	50 cm	70 cm
0	114	114	124	124	136	136	149	149
1	95	96	115	116	133	134	150	152
5	43	46	61	65	82	87	108	114
10	17	19	26	29	41	45	61	67
15	6	7	11	13	22	25	33	38

As already briefly mentioned, depth dose is measured indirectly by using *phantoms*, that is, materials equivalent to tissue in their absorption and scattering of x-rays. Water, rice, a mixture of rice and flour, ground meat, Columbia wax, and presswood are all examples of fairly good phantoms. In taking the readings given in Table XXVI, the special ionization chamber used by Mrs Quimby was backed by a mixture of rice and flour. Similarly in evaluating the depth doses given in Table XXVII, results also due to Mrs Quimby, the chamber was embedded in a phantom of this kind. In this connection we quote Mrs Quimby, "It is important that measurements used

for determining tissue doses shall have been made in phantoms comparable in size with the part of the body undergoing treatment. The use of data obtained with large phantoms to specify doses in smaller portions of the body, such as the limbs or neck, may introduce errors because of the difference in the actual amounts of scattering materials in the two cases."

The measurements recorded in the above table were taken using 200 Kv, constant potential rays, with a HVL equal to 1 mm copper, after being filtered with 0.5 mm of copper. The 50 cm and 70 cm at the top of alternate columns give the distance from the target to the skin (or surface of phantom). It will be noticed that at the same distance below the surface the values of the depth doses are different for different target distances. At 10 cm depths, for example, with the 25 sq cm field, the doses are 26 and 29 units. In all cases, a somewhat greater depth dose is delivered at the same depth in the case of the longer target distance. Since the greater the percentage of the surface dose delivered at the diseased tissue, the less the absorption by the intervening tissue, it is obviously an advantage to have as high a percentage depth dose as possible. Now calculations based on the inverse square law, as well as the numbers in the above table, show that the greater the target skin distance, the higher the percentage of the depth dose at any given distance below the surface.

It is now easy to see how the inverse square operates. Suppose that *F*, Fig. 160A, is a source of radiant energy of any kind and that we compare the values of the intensity of the radiation at places *A*, *B*, *C*, *D*, which are 50,

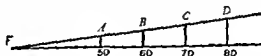


FIG. 160A. *F* represents the focal spot from which a narrow cone of rays spreads out

60, 70 and 80 cm, respectively, from the source. If the intensity at *A* is 100 units, the intensity at *B*, provided there is no absorption between *A* and *B*, is  $100 \times 50^2/60^2$ , or 69.6 units, at *C* the intensity is  $100 \times 50^2/70^2$ , or 51.1 units, and at *D*,  $100 \times 50^2/80^2$ , or 39.1 units.

Hence, if we increase the distance from the source by 10 cm, the intensity falls to 69.6 per cent when we go from 50 cm to 60 cm, but to 39.1/51.1 or 77 per cent when we go from 70 cm to 80 cm.

As far as the inverse square law is concerned, it is, therefore, a distinct advantage to use large target skin distances. On the other hand, the greater this distance, the smaller is the intensity of the x-ray beam, and hence the

longer the time it takes to build up the required number of roentgens, that is, the longer the time of treatment in deep therapy. In choosing the most favorable target distance, a compromise must be made between the gain arising from the increase in percentage depth dose, and the loss due to increased time of treatment. In this connection we again quote Mrs. Quimby, "From a practical point of view, this increase in time is an important economic factor. From a biological aspect, it introduces complications because of differences

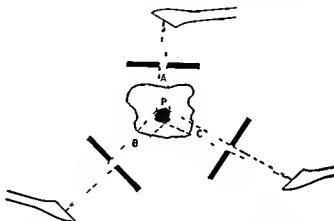


FIG. 161 To illustrate the method of cross fire treatment

in tissue recuperation." And, again, "it is not advantageous to use distances greater than ten or twelve times the known depth."

A second and more important method of reducing the absorption by the skin and intervening tissue in deep therapy consists in using *cross-fire treatment*. The principle of this method is simple and will be clear after a glance at Fig. 161, where *P* represents a diseased region within the body treated through three *ports of entry*, at *A*, *B*, and *C*. If the desired dose is delivered in three parts, one through each port, the absorption by healthy tissue is reduced about one third.

**161 Tolerance Dose** — The necessity of adequate protection from undue exposure to x rays has already been emphasized. In this connection, there is naturally a certain daily dose which represents the maximum permissible amount to which any x-ray worker should be exposed. At present this tolerance dose, as it is called, is generally taken as 0.1 roentgen per day. Unless rigid precautions are taken this small amount of radiation can easily

be exceeded in these days of supervoltages and beams of x rays of high intensity. A further reference to this question will be found in section 164 below.

**162. Isodose Curves and Charts** — The numbers in Table XXVII give dosage values at distances below the surface for various depth *along the axis* of the primary beam, but, for any given depth do not apply to points away from the axis. Depth dosages at such points, that is, at any place throughout the irradiated region in a phantom can be measured readily by means of the ionization chamber. From such measurements charts like those shown in

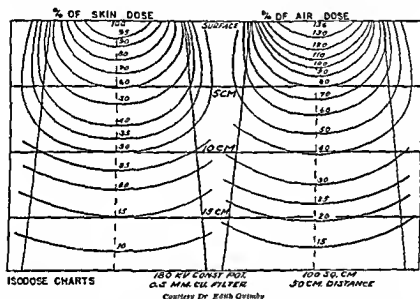


FIG. 162. Isodose charts for 180 kv constant potential filter 0.5 mm copper, 50 cm focal distance field 100 sq cm

Fig 162 can be constructed. In these charts a single curved line joins all points for which the dose is the same, hence the name *isodose curve*. The curves in this figure, reproduced through the courtesy of Dr Edith Quimby, apply to the following set of conditions: x-rays generated by 180 kilovolts, filter = 0.5 mm of copper, target distance = 50 cm, diameter of field at surface = 100 sq cm. A separate chart must be made of course, for each set of conditions.

Given the appropriate conditions, if one knows the surface dose at the center of the field, one can read off or quickly evaluate the correct corresponding dose

at any point within the charted area. It will be realized that, although the chart depicts only a single plane, it applies to the whole volume obtained by rotating it about the central axis.

**163 Threshold Erythema Dose.**—In deciding to what extent it is safe to irradiate the skin, a knowledge of the biological action of the skin to x-rays is necessary. In this connection much use is made of the *threshold erythema dose* (T E D), or the quantity of x-radiation which produces a mild skin erythema\*. This biological unit has played an important part in the development of x-ray dosimetry, because, whatever the physical method used to measure a quantity of x radiation, it has always been necessary to know something of a corresponding biological action. Thus, in the pastille method of dosage, Tint B corresponded to a unit skin dose, in the method of estimating quantity by the blackening of a strip of photographic paper, 10x arbitrary units corresponded to this unit, and so on for the other early methods. Now that dosimetry has advanced to the stage where the roentgen is the universal unit, all that is necessary is a knowledge of the T E D in roentgens. Since a much greater fraction of the radiation delivered at the skin is absorbed by the layer of tissue just below the surface when the x-ray beam is soft than when it is hard, the value of the T E D depends on the wave length. As its value also depends on the area radiated (that is, on the amount of back scatter) and to some extent on the individual patient it cannot be given with the accuracy of a physical constant. Some idea of its magnitude, however, is given by the following. Using 200 Kv rays, at constant potential, with H V L equal to 1 mm of copper, with a field of 100 sq cm, and with radiation given at a fairly high intensity in one setting, Mrs. Quimby gives the value of the T E D as 500r units in air, or 680r units on the skin. Dr. J. C. Hudson, of the Collis P. Huntington Memorial Hospital, Boston, after an examination of a number of radiology centers in the New England States, reports the numbers given in Table XXVIII, as the value of the T E D for four different qualities of rays, and with an area of 100 sq cm.

\* Mrs. Quimby gives the following definition. We define our threshold erythema dose as that amount of radiation which, delivered at a single sitting, will produce in 80 per cent of all cases a faint but definite reaction and in the other 20 per cent no visible change. We used to say within two or three weeks but we find that the proper time interval depends on the quality of the radiation. Three or four weeks is right for 200 kv, for lower voltages a shorter time is sufficient, but for gamma rays it may be six weeks. The reaction may never be red, but appear as a tanning. The term *erythema reaction* is not a good one, I prefer to call it threshold reaction, without including the term erythema. If you insist that redness shall appear first the question becomes very complicated.

TABLE XXVIII — AVERAGE VALUES IN ROENTGENS ON THE SKIN OF THE THRESHOLD ERYTHEMA DOSE FOR FOUR QUALITIES OF X RAYS

Wave Length	TE D	Absorption by the First Millimeter of Superficial Tissue
0.17 angstrom	965	18
0.22	800	17
0.27	640	16
0.42	425	16

The results of the last column were calculated using absorption coefficients  $\left(\frac{\mu}{\rho}\right)$  for water, and show, to quote Dr Hudson, "that the difference in dose necessary for an erythema at the various wave lengths is due chiefly to the difference in absorption by the tissue," and that "the total energy absorbed in the superficial layers of skin is practically constant"

#### 164. Relation of the Roentgen to Energy Measurements.\* —

Suppose a beam of x-rays strikes the area *AB*, Fig 163, on the skin of a patient, and that treatment is to be given a small tumor at *P*, at a known distance below the surface. As we have seen above, with the aid of depth dosage tables and isodose charts, the radiologist can find without difficulty the dose in roentgens at *P* corresponding to each 100r delivered in air at the surface. But the biological effect on the patient depends on the actual amount of energy absorbed, not only by the tumor, but also by the whole irradiated region around it. Radiologists are very familiar with radiation sickness and will realize readily that the dosage question is not completely solved until it is possible to obtain an accurate knowledge of the energy absorbed by all parts receiving radiation.

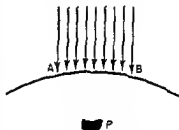


FIG 163 The arrows represent x rays used to treat a tumor at *P*

This is not an easy question to solve, but physicists like Failla and Mayneord and their co-workers have devoted a great deal of effort to its solution and much progress has been made. A detailed discussion of this problem is beyond the scope of this book, but the following brief outline will indicate the fundamental importance of the work and the way in which Mayneord and his associates, for example, are relating the roentgen to true energy absorption.

\*This section may be omitted in a first course.



(a) *The Gram-Roentgen* From the standpoint of energy the roentgen is equivalent to the amount necessary to produce in 1 cubic centimeter of air (at 760 mm pressure and  $0^{\circ}\text{C}$ ), or in 0.001293 gm of air, ions of either sign whose total charge is equal to 1 statcoulomb

Since the charge on a single ion  $= 4.8 \times 10^{-10}$  statcoulomb, the number of ions carrying a total charge of 1 statcoulomb  $= 1/(4.8 \times 10^{-10})$ , or  $10^{10}/4.8$ , or approximately  $2 \times 10^9$ . Hence, we might define a roentgen as that quantity of radiation which produces in 0.001293 gm of air,  $2 \times 10^9$  ion pairs. (For every positive ion there is of course a particle with an equal negative charge.)

Now careful investigations have shown that the energy necessary to produce 1 pair of ions in air is 33 electron-volts, or  $\frac{33 \times 4.8 \times 10^{-10}}{300}$  erg\*.

Therefore, the energy necessary to produce  $10^{10}/4.8$  ion pairs

$$= \frac{33 \times 4.8 \times 10^{-10}}{300} \cdot \frac{10^{10}}{4.8} = 0.11 \text{ erg}$$

It follows that 1 roentgen corresponds to an energy absorption of 0.11 erg per 0.001293 gm of air, which is the same as

$$0.11 \times \frac{1}{0.001293}, \text{ or about 85 ergs per gm}$$

Mayneord suggests that this unit, the energy absorption per roentgen per gram of air be called by the logical name 1 gram-roentgen

$$1 \text{ gram-roentgen} = 85 \text{ ergs}$$

If the reader will recall that 1 calorie  $= 4.2 \times 10^7$  ergs, he will realize that the gram roentgen is an extremely small unit of energy. A suitable larger unit is the megagram-roentgen, or a million gram-roentgens, which simple calculation shows to be equal approximately to 2 calories.

Since as far as energy absorption or conversion is concerned, soft tissues are approximately the same as air, the gram-roentgen in air may conveniently be used as a unit for tissue absorption.

(b) *Distribution of Energy Absorbed Throughout a Radiated Volume* Consider a small mass of  $m$  grams at a region  $M$ , Fig. 164, which lies anywhere in a beam of x-rays traversing soft tissue, or a phantom like water. Then, if the depth dose at  $M$  is  $D$  roentgens, the energy absorbed by the mass  $m = D \times m$  gram roentgens  $= 85Dm$  ergs. This assumes

\* Recall that the charge on an electron or a singly charged ion is  $4.8 \times 10^{-10}$  statcoulomb and that 300 volts  $= 1$  statvolt.

per cent curves. This is because at the lower dosage values the volume between two isodose curves which differ by 10 units is much greater than between two similar curves at the higher values. Note again Fig. 164.

By taking the volumes between *all* the isodose curves from the surface down to the 10 per cent level (only some of which are given in Table XXIX), the total integral dose down to this level is found at once by adding up all the numbers which would appear in the last column had every successive pair of isodose curves been used. In the particular set of conditions to which Table XXIX applies, the grand total is 96,560 gram-roentgens.

Mayneord and his associates have obtained similar data for x-rays of different kinds. A few of their results are given in Table XXX, where, for purposes of comparison, a set of readings relating to gamma rays from radium is included. Note the tremendous range in the magnitude of energy absorption, down to the 10 per cent curve, with different conditions, but always for the same skin dose of 100 roentgens (with back scatter).

TABLE XXX — GIVING THE ENERGY ABSORBED PER 100r AT THE SURFACE BETWEEN THE SURFACE AND THE 10 PER CENT LEVEL

Kilovolts	Filter	Wave Length	Focal Distance	Diameter of Field	Gram roentgens to 10% Level
60	Tube only	0.33	5.0 cm	4 cm	4,200
200	1 mm Cu	0.12	50.0 cm	10 cm	96,560
400	4 mm Cu	0.069	50.0 cm	10 cm	110,000
Gamma rays	1 mm Pt	0.014	5.0 cm	5 cm	14,593

(c) *Total Integral Dose per Year per Man Subjected to the Tolerance Dose.* Another interesting example of the energy viewpoint has to do with the total energy absorbed during a long time interval, a year, for example, by a person subjected to the tolerance dose continuously.

Let the mass of the person = 150 lbs = 68,000 gm

If we take the tolerance dose = 0.1r per day, the total energy absorbed by such a person in 1 year =  $0.1 \times 365 \times 68,000$  gram-roentgens  
 $= 2.5 \times 10^6$  gram roentgens approximately

Now we have seen that the total integral dose *per 100 roentgens* on the surface, for 200 kilovolt rays and the other conditions applicable to Table XXX

= 96,560 gram-roentgens

=  $10^5$  gram roentgens, approximately.

Since  $2.5 \times 10^6$  is 25 times greater than  $10^5$ , we see that the total integral

dose, or energy absorbed by a person subjected to the tolerance dose during one year, is equivalent to  $25 \times 100$  roentgens, or 2500 roentgens delivered to the skin with 200 kilovolt rays, a field of 10 cm diameter, etc. This suggests, on the one hand, that a very weak roentgen dose delivered for a very long time has not the same effect as a strong dose for a corresponding short time, and, on the other, that it is not advisable for a worker to be exposed continuously, even to dosages within the tolerance limit.

(d) *Relation of Energy Flux through Unit Area to a Dose in Roentgens* Let  $ABCD$ , Fig. 165, represent a thin section of air whose faces  $AB$  and  $CD$  are 1 sq cm in area, and whose thickness  $AC = BD = x$  is a small fraction of a centimeter. Suppose that a beam of x-rays of uniform intensity across  $AB$  delivers a dose of  $D$  roentgens at the center of the thin section.

Then the energy absorbed in the volume  $ABCD$

$$\begin{aligned} &= D \times m \text{ gram roentgens} \\ &= 85 \times D \times m \text{ ergs,} \end{aligned}$$

if  $m$  is the mass of the volume  $ABCD$ .

Now let  $E_0$  = the total energy in ergs which has passed through the area  $AB$ , that is, the flux of energy per sq cm, during the time  $D$  roentgens was delivered to the section. Of this total energy, equal to  $E_0$  ergs, only a portion is absorbed by the mass  $m$ , because a part, which may be large, is either transmitted, or truly scattered. Hence we can write

$$E_0 \times \text{fraction absorbed} = 85 \times D \times m$$

Now if  $\mu$  is the true absorption coefficient and  $\rho$  the density of the air, we can write (see section 136)

$$\begin{aligned} \text{energy transmitted} &= E_0 e^{-\mu x} \\ &= E_0 e^{-\frac{\mu}{\rho} m} \\ &= E_0 \left(1 - \frac{\mu}{\rho} m\right) \end{aligned}$$

provided  $m$  is small, as it is for a thin section

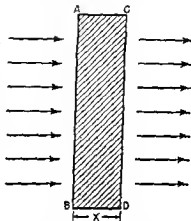


FIG. 165  $ABCD$  represents a thin section of absorbing material traversed by x rays

$$\begin{aligned}\text{Therefore, energy absorbed} &= E_0 - E_0 \left(1 - \frac{\mu}{\rho} m\right) \\ &= E_0 \frac{\mu}{\rho} m,\end{aligned}$$

where  $\frac{\mu}{\rho}$ , it will be recalled, is the true mass absorption coefficient

It follows that

$$E_0 \frac{\mu}{\rho} m = 85 \times D \times m,$$

$$\begin{aligned}\text{or,} \quad E_0 &= \frac{85 \times D}{\mu/\rho} \text{ ergs per sq cm} \\ &= \frac{85}{\mu/\rho} \text{ ergs per sq cm per roentgen}\end{aligned}$$

The value of  $\mu/\rho$  for air varies tremendously, with the wave length of the x-rays used, depending as has been pointed out in section 137, on the energy absorbed to produce both photo and recoil electrons, as well as on scattering. Since we are here concerned with energy conversion, that is, true energy absorption,

$$\frac{\mu}{\rho} = \frac{\sigma_a}{\rho} + \frac{\tau}{\rho}.$$

For wave lengths of 0.1 A.U. or less,  $\sigma_a/\rho + \tau/\rho$  has a mean value of about 0.028. Hence, for such wave lengths, an energy flux of about 85/0.028 or 3000 ergs per sq cm must be delivered on a surface to give rise to a dose of 1 roentgen. For longer wave lengths, the energy flux per roentgen is considerably less, the magnitude falling off rapidly as the wave length exceeds 0.15 A.U. For example, according to published work of Mayneord, for  $\lambda = 0.2$ , the flux per roentgen is 2000 ergs per sq cm, for  $\lambda = 0.25$ , 1175 ergs per sq cm, for  $\lambda = 0.3$ , 820 ergs per sq cm, and for  $\lambda = 0.35$ , about 600 ergs per sq cm.

From these numbers, one can draw an important conclusion regarding desirable protection. Suppose a person is subjected to a tolerance dose of 0.1 r per day because of stray radiation, (a) from a low voltage machine emitting a mean wave length of 0.3 A.U., or (b) from a high voltage machine emitting 0.1 A.U. In case (b) the energy which each day passes through each sq cm of the person's body (where most of it will be absorbed) is about 300 ergs, whereas in case (a) the equivalent amount of energy is

only about 82 ergs. It follows that for adequate protection the tolerance dose should be less for workers exposed to radiations of short wave length than for exposure to fairly long wave lengths. In days of supervoltages and 100 million electron-volt machines this is a matter of considerable importance.

**165 Specifications of Treatment Conditions** — Much more might be said about the important question of dosage, but it is hoped that enough has been given to make clear the important underlying physical principles and to enable the radiologist to build on the foundations which have been laid in this chapter. To sum up, we conclude with an extract from the recommendations of the International Committee for Radiological Units at the 1937 meeting.

"The specifications of treatment conditions shall include the following

- I *Quantity* — The quantity of radiation (expressed in roentgens) estimated to have been received by the lesion
- II *Quality* — (a) The spectral energy distribution of x radiation shall be designated by some suitable index, called quality. For most medical purposes it is sufficient to express the quality of the x-radiation by the half value layer in a suitable material. Up to 20 kilovolts (peak) cellophane or cellone, 20–120 kilovolts (peak) aluminum, 120–400 kilovolts (peak) copper, 400 kilovolts (peak) up tin. For a more definite specification of the quality of the radiation the complete absorption curve in the same material is preferable. (b) Material and thickness of filter, including tube walls. (c) Target material
- III *Technic* — (a) Total quantity of radiation per field (incident and emergent) received in an entire course of treatment. (b) Quantity of radiation per field measured at the surface ( $D_s$ ) at each individual irradiation. (c) The dosage rate expressed in r/min during each individual irradiation. (d) The total time over which a course of treatments is spread. (e) The time interval between successive doses. (f) The target skin distance. (g) The number, dimensions, and location of the ports of entry."

## PROBLEMS AND QUESTIONS

- 1 (a) Make a diagram showing the electric connections when a standard ionization chamber and a galvanometer are used to compare the intensities of x ray beams.
- (b) If in a standard chamber ions were taken from a volume of 10 cc and a current of  $10^{-9}$  ampere was recorded by a galvanometer, what is the intensity of the beam in r units per second?

2 Why must a small ionization chamber be calibrated by means of a standard chamber if measurement in  $r$  units is required?

3 How does the intensity of a beam of  $x$  rays at a given place depend on (i) the distance from target, (ii) the voltage across the tube, (iii) the tube current?

4 When a small ionization chamber (joined to an electroscop) is placed in a beam of  $x$  rays at a place 25 cm from the focal spot, the electroscop falls at the rate of 2.1 divisions per second. What is the rate of fall if the chamber is removed to a distance of 60 cm? *Ans* 0.36 div per sec

5 A steadily increasing voltage is applied to two plates between which a narrow strip of air is kept ionized by a beam of  $x$  rays of constant intensity. Describe, with simple graph and explanation, how the current between the plates alters with the voltage.

6 How would you show experimentally that water is a good phantom for tissue?

7 A small ionization chamber is used to measure the intensity of an  $x$  ray beam at a certain focal target distance, (i) in air, (ii) when the chamber rests on a thick block of paraffin, (iii) when the chamber is completely surrounded by paraffin. Intensities of 28, 43, and 35 units are obtained. Discuss and explain these results.

8 Describe an experiment to show that in deep therapy, scattered rays may be the cause of a greater intensity at the place treated than the primary beam.

9 The natural leak of an electroscop of capacity 10 statfarads is 0.5 division per minute. Find the natural leak, if the insulated plate of a condenser of capacity 200 statfarads is attached to the insulated system of the electroscop, the outer case of the electroscop and the other plate of the condenser being grounded. *Ans* 0.238 div per min

10 In a standard ionization chamber, ions are driven to a collecting electrode from a volume of 10 cc. The capacity of the electrode and attached electrometer system is 800 statfarads. If the intensity of the  $x$  ray beam is 0.4  $r$  units per second, find the change of potential (in volts) of the electrometer system in 5 minutes. (1 farad =  $9 \times 10^{11}$  statfarads). *Ans* 450 volts

11 Make a diagram showing how a small ionization chamber can be used in connection with an electroscop. Indicate what parts are insulated and what grounded.

12 Define the roentgen and show, with diagram, how by means of a standard ionization chamber, the intensity of a beam in  $r$  units per second may be found.

13 Explain what constitutes a good "phantom" for  $x$ -rays in therapy, and name one suitable substance.

14 In deep therapy why is a filter always used between the patient and the target of the tube?

15 An electroscop is joined to the insulated plate of an  $x$ -ray standard parallel plate ionization chamber (whose other plate is grounded) and the insulated system, whose capacity is 1/1000 microfarad, is charged until its potential is 900 volts. (i) What is the total charge in coulombs on the insulated system? (ii) A parallel beam of  $x$  rays passes between the plates of the chamber and ions are driven to the insulated plate from a volume of 30 cc. If the intensity of the beam of  $x$  rays is  $\frac{1}{2}$  roentgen per second, find how long it will take to discharge the electroscop (and attached plate).

$$1 \text{ microfarad} = 900,000 \text{ statfarads, } 300 \text{ volts} = 1 \text{ statvolt,}$$

$$1 \text{ coulomb} = 3 \times 10^9 \text{ statcoulomb}$$

*Ans* (i)  $9 \times 10^{-7}$  coulomb; (ii) 3 minutes

16 In an ionization chamber, why must the voltage between the two electrodes exceed a certain minimum amount?

17 A tumor 10 cm below the surface is treated under the following conditions: Port of entry = 25 cm, Voltage across tube = 200 kv, Tube current = 5 ma, Filter = 0.75 mm Cu + 1 mm Al, Target skin distance = 30 cm, Effective wave length = 0.15 Å, Percentage of surface intensity = 40 per cent. Discuss the importance of each factor.

18 Discuss the importance of the size of the port of entry in using x rays for therapy.

19 The insulated electrode of an ionization chamber is joined to an electroscope, the capacity of the system being 10 e.s.u. units. When an x ray beam of a certain intensity ionizes the air in the chamber, the leaf of the electroscope falls at the rate of 5 divisions per second. When a condenser is attached to the insulated rod of the electroscope, and an x ray beam of equal intensity is used, it takes one hour for the leaf to fall 25 divisions. Find the capacity of the condenser. *Ans.* 7190 e.s.u. units.

20 Make a diagram showing how a thimble ionization chamber might be used in conjunction with an electroscope for comparing x ray intensities. Give two reasons why such an arrangement does not necessarily allow you to evaluate intensities in r units per second.

21 Describe briefly, listing successive steps, the use of the Victoreen condenser meter for measuring an x ray dose in roentgens.

22 What condition must be fulfilled, if an ionization chamber is to be described as "air wall"? How is this condition obtained practically?

23 How would you show experimentally the existence of "back scatter"?

24 The volume in which ions are produced by an x ray beam in a standard ionization chamber is 20 cc. If the intensity of the beam in the chamber is 0.4 r per second, find how many ions (of either sign) go to the collecting electrode in 1 minute.

25 Why is the skin dose corresponding to a certain air dose (1) greater than the air dose, (2) greater for a beam of large aperture than for one of small aperture?

26 Why is the T.E.D. (expressed in r units on the skin) greater for wave length 0.2 angstrom than for 0.25 angstrom?

27 In a standard ionization chamber, ions are driven to a collecting electrode from a volume of 10 cc. and the capacity of the electrode and attached electrometer system is  $10^{-8}$  farad. When a certain x ray beam traverses the chamber, the potential of the electrode and attached system changes at the rate of 2 volts per second. Find the intensity of the beam in r units per second.

## CHAPTER XIV

### RADIOACTIVITY

166 The Discovery of Radioactivity. — The middle of the last decade of the nineteenth century was one of the most fruitful periods in physical science which has ever existed. Within two or three years, the electron, x-rays, and radioactivity were all discovered. These were by no means independent discoveries because in science, as in life, one thing often leads to another. A good example of this is found in the discovery of radioactive substances. The walls of gas x-ray tubes strongly fluoresce and in the early days it was not unnatural to associate the origin of these invisible rays with the fluorescence. With this idea in mind, Becquerel, a French scientist, tried to see if certain compounds of the element uranium would emit x-rays after being made to fluoresce by exposure to light. He was rewarded by finding an invisible radiation, but was soon able to show that it had nothing to do with x-rays. The uranium compound in its normal state, that is, without any stimulus by light or by anything else, was found to emit something which passed through a sheet of black paper and affected a photographic plate behind the paper. This emission, moreover, was perfectly spontaneous. Neither heat nor cold could start or stop it. It was a natural property of the compound.

This original discovery made in 1896 was followed by rapid developments and it was not long before it was found that residues of pitchblende, one of the ores in which uranium is found, were much more radioactive than pure uranium compounds themselves. In 1898 Madame Curie, the Polish wife of a French physicist, with the assistance of her husband, isolated polonium and radium, two substances possessing radioactive powers in a remarkably high degree. Radium was shown to be an element of atomic weight 226 with chemical properties similar to the stable element barium.

It is, however, with the nature of radiations emitted by a radioactive substance that we are specially concerned, not with its chemical properties. The radiations, whatever they are, have three outstanding properties. They ionize the air, or any gas, through which they pass, they affect a photographic plate like light or x-rays or positive rays, and they cause fluorescence when they strike certain substances. The ionization effect will detect such a small quantity of radioactive substance that it has been of great importance throughout the whole development of the subject, the photographic effect led to



Becquerel's discovery, and the ability of the rays to excite fluorescence is probably familiar to most people because of the radium-coated watch hands which may be seen in the dark

**167 The Nature of the Radiations.** — In seeking to find out the nature of the radiations emitted by a substance like radium, it was natural that early investigators should examine what happens when the rays traverse a magnetic field. The deflection of cathode rays by a magnetic field had shown that they were negatively charged particles. What did such a test show when radioactive radiations were examined? In principle the experiment is extremely simple. A narrow beam of rays emerging through the top of a containing box *B*, Fig. 166, passes through a magnetic field between *N* and *S*. By such a means the original beam is separated into three components: (1) a portion undeflected by even the strongest magnetic field, (2) a second part readily deflected in the direction which indicates that it must consist of negatively charged particles, and (3) a third part, consisting of positively charged particles, deflected a slight amount in the opposite direction by sufficiently strong fields. The positive particles are called alpha rays, the negative beta, and the undeflected beam, which is of a non-corpuscular nature, gamma rays.

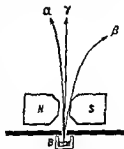


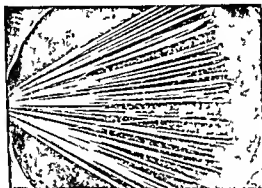
FIG. 166 A magnetic field separates the radiations from radium into three groups. The deflection of the  $\beta$  beam is towards the observer, of the  $\alpha$  beam away from him.

Once we know that we are dealing with a flight of particles, certain questions at once suggest themselves. What is the mass of each of these particles? What charge do they carry? How fast do they move? How penetrating are they? As always, experiment provides the answer to these questions. In the following sections, important details are given concerning each kind of radiation.

**168 Alpha Rays** — (1) As already noted, alpha rays are positively charged particles. Experiment shows that the magnitude of the charge carried by each particle is equal to two electronic units, that is, it is exactly twice the charge on a proton.

(2) Measurements of the amount of the deflection produced by magnetic and electric fields (see section 35), combined with a knowledge of the magnitude of the charge, show that each alpha particle has a mass about four times that of a hydrogen atom. Combining (1) and (2) we see that this particle is essentially an atom of atomic weight 4 and atomic number 2.

(3) Alpha rays cause intense ionization as they traverse a gas. This is beautifully shown by cloud track photographs (see section 131), such as are reproduced in Fig 167 and Fig 168. In Fig 167 each white line represents the path of a single alpha particle. In its flight it causes such intense ionization that the little droplets formed on ions are so close together that they give rise to an unbroken continuous streak of light. On the average an alpha particle makes about 3000 ion pairs per millimeter of its path.



*Courtesy V. Feather and the Royal Society*

FIG 167 Cloud track photograph showing a shower of alpha particles ejected from a small source

The photograph of Fig 168 shows the tracks of but two alpha particles. In the left hand track of this figure it will be noted that the path turns through a small angle to the right and then just before the end of the track, it makes a second and much sharper turn to the left. These sudden turnings are evidence of the near approach of the alpha particle to the nucleus of an atom. Ordinarily this heavy particle ploughs along without being deflected out of its path even when passing right through an atom. Occasionally, however, the particle in its passage through the atom passes so near the nucleus that its direction is altered as shown in the photograph. The study of such deflections, that is of *scattering* when alpha rays strike a thin sheet of gold led to estimates of the size of the nucleus, and to the picture of the atom we have given in section 36.

On rare occasions an alpha particle strikes a nucleus 'head-on,' and in such cases things happen as we shall see later. (See section 179.)

Tracks of particles may also be revealed by the use of the photographic emulsion on a plate or film. If for example an alpha particle traverses such an emulsion on development of the plate or film its track is readily visible

Since the tracks of such particles in emulsions are extremely short, the photographic reproduction is usually highly magnified. A good example of such an alpha ray track is seen in the left side of Fig 205, the reproduction of a photograph kindly given the author by Dr Pierre Demers, of the University of Montreal.

(4) When they strike certain substances, alpha rays cause marked fluorescence, a property which is made use of in the spintharoscope, one of the early radioactive toys. In this arrangement, a speck of radioactive material is placed near a screen coated with zinc sulphide and, with eyes rested, the screen is viewed through a magnifying glass in a darkened room. Little flashes of light are seen to dance about in irregular fashion, somewhat as if in a patch of sky the stars kept disappearing in one place and reappearing in another. Each scintillation corresponds to the impact of an alpha particle on the screen. We have called this a toy but, as a matter of fact it was the basis of more than one investigation in which the number of alpha particles leaving a source in a given time was counted, and it was used with success in determining how far both alpha particles and protons travel before they are no longer able to ionize.

(5) Alpha rays have a speed which varies with the radioactive source from which they are emitted, but for the most part is between one fifteenth and one tenth of the velocity of light. It is worth noting that alpha particles, whose speed is a little less than one-twentieth of the velocity of light, have about four million electron volts (4 mev) of energy. Alpha particles are emitted from some sources with energies as high as 8 mev. In Fig 167 it will be noted that the tracks come to an abrupt end. This is due to the fact that once the velocity falls below a certain value, an alpha particle is no longer able to ionize. The actual range in air over which they can ionize is only a few centimeters never more than 8.6 cm.



Courtesy C. T. R. Wilson and the Royal Society

FIG 168 Cloud track photograph of paths of two alpha particles

(6) It follows from this that alpha rays are readily absorbed by solids. They are completely cut off by a sheet or two of ordinary paper, or by a thickness of about 0.006 cm of aluminum, and they cannot get through 0.1 mm of epithelial tissue. It will be evident, therefore, that if a radioactive substance is enclosed in a glass tube (unless extremely thin), alpha rays will not get through the glass.

To examine the alpha ray emission from a substance, an electroscope of the type shown in Fig. 169 is used. The insulated rod of an electro-

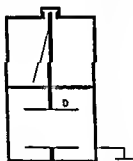


FIG. 169 An alpha ray electroscope

scope extends, through insulating material, into the lower chamber, where it is attached to a disc *D*. The radioactive material, placed on the earthed platform, gives off radiations which ionize the air in its vicinity. When the electroscope is charged, the leaf falls at a rate which is proportional to the amount of ionization, and hence to the quantity of radioactive material.

169 Beta Rays — (1) Beta rays are nothing but high speed electrons shot out of radioactive substances with velocities which cover a wide range, but may exceed nine tenths of the velocity of light. To acquire a speed equal to the fastest beta ray — over ninety-nine per cent of the velocity of light — a cathode ray would have to fall through a potential difference of over three million volts.



Courtesy of T. R. Wilson and the Royal Society

FIG. 170 Cloud track photograph of a fast beta ray. The irregularly curved line of dots arises from a slowly moving electron.

(2) Beta rays ionize a gas, although not so intensely as alpha rays. The difference will be evident by a comparison of Fig 170 with either Fig 167 or Fig 168. In Fig 170 the straight line of tiny dots marks the path of a beta ray moving so quickly that it is not deflected out of its path. On the same photograph the curved irregular path near the middle is due to a slow electron which is easily turned aside by collisions. The student should also examine Fig 196, where the photograph shows very beautifully the curved path of an ionizing particle like a beta ray or an electron when it is constantly deflected by the presence of a magnetic field. By way of comparison with an alpha particle, note that a beta ray creates from 10 to 20 ions per millimeter of its path.

The type of electroscope shown in Fig 123 may also be used for studying beta ray ionization. If the radioactive material is placed outside the window *W*, a moderate thickness of paper will exclude alpha rays. Alternately, the window can be removed, the metal wall of the container being continuous, and the chamber can be designed so that a tray containing the radioactive material can be placed inside, at the bottom. Here again, a sheet of paper of suitable thickness can be used to remove the alpha rays.

(3) Beta rays being of small mass and of high speed, are much more penetrating than alpha rays. The fastest will pass through several millimeters of a low density metal or of tissue, and traverse as much as ten feet of air before they are stopped. They are, however, completely stopped by less than 0.5 mm of gold or of platinum, or by about 0.4 mm of steel or monel metal\*. It will be seen then, that, by placing a radioactive substance in a suitable container it is not a difficult matter to remove both beta and alpha rays.

**170 Gamma Rays** — (1) Gamma rays are electromagnetic waves of the same nature as x rays, but for the most part of shorter wave length. The actual values of emitted wave lengths depend on the radioactive source, and for a given source more than one wave length is emitted. From radium C, for example (see section 178), there are waves as long as 0.2 angstrom, a value in the therapy x ray range, and as short as 0.0056 angstrom.

(2) Some gamma rays are so penetrating that a thickness as great as 10 cm of lead will not completely absorb them. A thickness of platinum or of gold equal to 0.5 mm, which we have seen completely absorbs beta rays, absorbs only about 7 per cent of the gamma rays emitted from a salt of radium enclosed in a tube. Muscular tissue, 2 cm in thickness, reduces the intensity only 5 per

\* For exact examination of the penetration of beta rays use is made of absorption coefficients and the relation  $I = I_0 e^{-\mu x}$  as in x rays.

cent, and even after traversing 20 cm, the rays emerge with over 60 per cent their original intensity

As with x rays, the actual absorption coefficient varies with the wave length but an average value enables the radiologist to estimate with sufficient accuracy for most purposes the absorption caused by various materials. In this connection the numbers given in Table XXXI\* are useful

TABLE XXXI — ABSORPTION COEFFICIENTS FOR GAMMA RAYS FROM RADIUM

Substance	Coefficient
Aluminum	0.007
Lead	0.088
Platinum	0.139
Gold	0.140
Monel	0.021
Brass	0.020
Muscle	0.0024
Epithelial tissue	0.0024
Bone	0.0055
Water	0.0026
Paraffin wax	0.0022

The coefficients given in this table are used in the same way as the linear absorption coefficients of x-rays, as explained in section 136, with the exception that when using the values given in Table XXXI, the thickness of the absorbing layer must be expressed in millimeters, not centimeters. Thus if  $I_0$  is the intensity of the gamma radiation from a radium salt incident on a layer of aluminum  $x$  mm thick,  $I$ , the emergent intensity, is given by the relation

$$I = I_0 e^{-\mu x} = I_0 e^{-0.007x},$$

or, by the equivalent relation

$$\mu = 0.007 = \frac{2.30}{x} (\log_{10} I_0 - \log_{10} I)$$

If the thickness of the absorber is small, these relations may be replaced, with very slight error, by the simpler expression

$$I = I_0 (1 - \mu x),$$

from which it follows that the

$$\text{fraction absorbed} = \mu x$$

\* Taken from Radium Dosage Bulletin No. 17 of the National Research Council of Canada By G. C. Laurence

For example, 1 mm. of aluminum absorbs about 0.007 or 0.7 per cent of the incident gamma radiation from a radium source, 0.5 mm. of gold about  $0.140 \times 0.5$  or about 7 per cent, 0.25 mm. of platinum about 3.5 per cent, and 1 mm. tissue about 0.24 per cent.

(3) Gamma rays ionize a gas through which they pass. This ionization is largely due to an emission of secondary beta rays which results whenever gamma rays traverse matter. Secondary beta rays may have velocities high enough to enable them to traverse several meters in air or a few millimeters in tissue before being stopped. This means that, when a radium salt is enclosed in a tube like platinum, of sufficient thickness to absorb completely the original beta rays, that is, the primary betas, the gamma rays will cause an emission of secondary betas from the platinum. In radium therapy it is therefore necessary to surround the metal with a secondary filter of such a material that it absorbs the objectionable secondary betas, and does not emit intense secondary beta rays itself. For this purpose, a material like rubber has been used to a considerable extent, although recently Quimby and co-workers have shown that "the secondary radiation is considerably less for substances of intermediate atomic number than for those toward either end of the atomic scale." Stainless steel or nickel, for example, are sometimes more suitable than rubber or celluloid.

✓ (4) When gamma rays traverse matter, a certain amount of scattering takes place, the amount depending on the quality of the primary beam and on the scattering material. The reduction of intensity when a primary beam traverses a layer of matter such as the walls of a metal tube containing radium is due, in part to scattering, in part to true absorption corresponding to the emission of secondary beta rays. The absorption coefficients given in Table XXXI take into consideration both of these factors.

Since gamma rays are of the same nature as x-rays, it should be evident from the discussion in section 132 that, with materials of low atomic weight, like air, water and tissue, secondary beta rays are almost entirely recoil electrons. Because of the shorter wave length of gamma rays (and hence the greater amount of energy  $h\nu$  in a photon of a gamma ray), the velocities of the secondary betas or recoil electrons are high enough to enable them, as we have seen, to traverse several meters in air. Gamma rays of wave length 0.02 angstrom, for example, give rise to recoil electrons with a maximum range of the order of 4 meters in air or 5 mm. in tissue.

If a beam of gamma rays is used for the treatment of deep seated tissue, the scattered rays from surrounding tissue add to the dose delivered to the region under treatment, or, in this case the effect of those scattered rays is to reduce the apparent absorption of the primary beam. Because of the true

absorption of energy represented by recoil electrons, the wave length of gamma radiation is increased after scattering, that is, the beam is softened (Read again sections 128 and 132)

(5) The electroscope illustrated in Fig 123 (with window replaced by metal) may be used conveniently for studying the relative intensities of the gamma radiations from two sources, provided that the thickness of the walls of the chamber is sufficient to absorb all the primary beta rays from the sources

**171 Geiger-Mueller Counters** — In section 168 a brief reference was made to an experiment in which the number of alpha particles leaving a source was counted by observers making use of scintillations. A much better method is provided by the use of an electrical counter, a device which has the additional advantage that it can be used for many other purposes, some of them of great importance in radiology

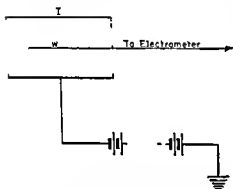


FIG 171 *I* represents an ionization chamber with central electrode *W* joined to an electrometer

Fundamentally counters make use of ionization and ionization chambers. To understand the basic principles, consider the specific problems of (a) detecting by an electrical method the entry of a single alpha particle into an ionization chamber,

and (b) of counting the number which enter in a given time. Suppose an alpha particle enters an ionization chamber *I*, Fig 171, consisting of an outer conducting cylinder maintained at a high negative potential and a central electrode *W* joined to a simple electrometer. As has been indicated, an alpha particle on the average creates some 3000 ion pairs per millimeter of its path in air at atmospheric pressure. Therefore, if its ionizing path in the chamber is, say 5 cm it will create  $3000 \times 50$  or  $1.5 \times 10^5$  ions. If we assume no recombination,  $1.5 \times 10^5$  particles, each with the electronic charge of  $4.80 \times 10^{-10}$  statcoulomb, will be driven to the central electrode, that is, it and the attached electrometer will acquire a negative charge of  $1.5 \times 10^5 \times 4.8 \times 10^{-10}$  or about  $6.4 \times 10^{-5}$  statcoulomb.

Since the capacity of the system acquiring this small charge is also small, the resulting change in potential is of the order of millivolts or even less. With an ordinary type of electrometer such a potential pulse, as we may call it, would not be observed. On the other hand, by joining the collecting elec



trode to a suitable vacuum tube circuit, for example, to the grid of an 6P54 tube, the arrival of the pulse due to the entrance of an alpha particle into the chamber can be registered and observed.

Now, suppose a succession of alpha particles enters a chamber, possibly a large number per second. What arrangement can be made to obtain a corresponding number of observable electrical changes per second? The answer to that question was first given in 1908 by Rutherford and Geiger, long before the days of electronic devices. Suppose that the voltage applied between the collecting electrode and the outer case of the chamber is made sufficiently high that the ions or electrons in their passage through the strong electric field near the electrode acquire enough energy to ionize by collision. In that case, each original electron or ion creates many more, because each of the second generation is speeded up to ionize by collision, the process being rapidly cumulative, so that the original  $1.5 \times 10^3$  ions is multiplied many times. Under such conditions, the pulse of potential given to the fibre of a string electrometer attached to the collecting electrode is great enough to be observed. This was the principle employed by Rutherford and Geiger who stated that "the current through the gas due to the entrance of an alpha particle into the detecting vessel was magnified . . . sufficiently to give a marked deflection to the needle of an electrometer of moderate sensitivity." Their "detecting vessel" was the parent of the modern counter.

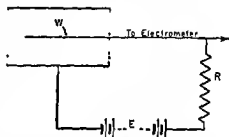


FIG. 172 When a large ionization current develops suddenly in the ionization chamber because of the drop in potential along the resistance  $R$ , the P.D. between the electrode  $W$  and the chamber wall drops suddenly.

In order to count a rapid succession of alpha particles, the cumulative discharge in the chamber following the entrance of a single particle must be quenched in a very short time. Obviously the shorter the time, the more rapid the counting which can be made. This book is not the place to go into details regarding quenching mechanisms, but one or two factors involved are worth noting.

Suppose a circuit is arranged as in Fig. 172, where  $W$ , a fine wire, is the collecting electrode,  $R$  a high resistance, and  $E$  the E.M.F. of the source used to create a potential difference between  $W$  and the wall of the chamber. With no ionization current, this P.D. is equal to  $E$  volts. But if the ionization current following the entrance of a particle suddenly rises to  $I$  amperes, then

this P D drops to  $E - IR$ . Hence, the strength of the electric field in the chamber quickly drops to a value, which, by proper choice of  $R$  and by suitable design of the chamber, is not great enough to maintain a discharge. Moreover, because negative electrons move much more rapidly than the heavy positive ions, during the period the ionization current exists, there is a rapid removal of electrons to the wire  $W$ , accompanied by a comparatively slow movement of positive ions towards the wall. This slow movement of positive ions gives rise to a positive space charge whose presence still further weakens the field near the wire  $W$  and assists quenching.

The beginner, however, need not be concerned greatly about quenching mechanisms, if he has grasped the essential ideas that the entrance of a single ionizing particle into a counter chamber can be observed and recorded, and that the corresponding ionization current in the chamber can be quenched so rapidly that the entrance of many particles every second can be counted.

By recording photographically on a moving film the movements of the fibre of a string electrometer, the entry of several hundred particles per minute can be recorded. Modern counters, however, make use of different types of vacuum tube circuits, some of which can record mechanically pulses as rapid as 3000 per second. For recording rapid pulses mechanically, so-called "sealing circuits" are used in connection with the counter. For example, the "scale of two" in common use, employs electronic devices designed so that a register is made for every 2 particles entering the chamber, or every 4, 8, 16, etc.

*Proportional Counter* Depending on the applied voltage between the central wire and the wall of the chamber, counters are used in two main ways (i) in the proportional region, (ii) in the Geiger region. A proportional counter is used with such a range of voltages that the flow of charge to the central electrode following the cumulative ionization, although many times greater than the initial number of ions created by the original ionizing particle is always proportional to this initial number. With such a counter, therefore, one can readily distinguish between the entrance into the chamber of a high speed electron or a beta ray and an alpha particle because of the much smaller number of ions created by the electron than by the alpha particle. The observed signal caused by the entrance of an electron will consequently be much less intense than in the case of the alpha particle.

*Geiger Mueller Counter* Beyond the range of voltage suitable for a proportional counter, there is a region of still higher potential differences such that the flow of charge to the central wire following cumulative ionization is independent of the number of ions created by the original ionizing particle, being just as great for a beta ray as for an alpha particle. A counter designed

for operation in this region is called a Geiger-Mueller, or sometimes simply a Geiger counter. In a properly designed counter of this type, there is a considerable range of voltages (the plateau region) such that the number of counts per minute recorded by the counting mechanism is independent of the actual value of the voltage, a necessary condition if the number of counts per minute is to equal the original number of particles entering the chamber each minute.

Geiger-Mueller counters can be used for many purposes, their construction and design naturally varying somewhat with the use to which they are put. The importance of suitable potential differences has already been indicated. Two other important variables are the nature of the gas in the chamber and the gas pressure. With regard to these factors there is considerable leeway. Pure gases like hydrogen, helium, nitrogen, have been used, also mixtures like argon-hydrogen, neon-hydrogen, argon and alcohol vapor, and various



FIG. 173 Ionization chamber for a Geiger-Mueller counter suitable for alpha particles

polyatomic gases, such as methane for example. The range of pressures is considerable, but for the most part fairly low, of the order of 13 cm  $\pm$  6 or 7 cm of mercury.

The construction of a Geiger counter, designed especially for alpha rays, is illustrated in Fig. 173, a diagram reproduced from the book *Electron and Nuclear Counters*, by Korff, by kind permission of the author and the publishers, D. Van Nostrand Company, Inc., New York. The glass window must be thin enough to permit the passage of alpha particles.

Of great importance to the radiologist is the fact that Geiger-Mueller counters can be used to detect and to measure x-rays and gamma radiation. This is possible because of the secondary electrons (photo or recoil) produced by these radiations. If a photon on entering a chamber causes the emission of a secondary electron, the electron can ionize along its path, and counter action is possible. Sometimes to increase the sensitivity of a counter for certain types of radiation, the wall of the chamber is coated with a material giving a marked photoelectric emission when struck by the radiation to be tested.

Reference to counters suitable for detecting and counting neutrons will be found in section 198

**172. Radium in Treatment.** — In therapy, radium is used in three important ways (1) A small amount of a radium salt is enclosed in a tiny tube or needle, made of such metals as steel, monel, platinum, platinum-iridium, and gold. Although radium can be obtained in the metallic state, normally it is used as a salt in the chloride, bromide, or sulphate state. This needle, or a pack consisting of a group of several needles, is then used as a source of radiation. Usually the filtration is sufficient to restrict the rays to gamma only, but with thin walls some primary betas can emerge. As already noted *secondary betas emerging from the metal container can be removed by additional filtration*

The amount of radium used in a single needle is of the order of a few milligrams. An applicator may be placed in contact with the tissue, or, if sufficiently powerful, at a few centimeters from it.

(2) In *radium beam therapy*, the source is a *bomb* containing several grams of this radioactive element. In this case the patient, or more accurately, the tissue under treatment, is subjected to an intense beam of gamma rays.

(3) *Needles or seeds of radon or radium emanation*, a radioactive gas manufactured by radium, are frequently used instead of the original radium salt. Small glass tubes containing the radon may be embedded or *implanted* in the actual tissue under treatment, or they may be placed within metal containers like the needles mentioned above. The difference between the use of radon and radium salt is explained below.

All the above methods, it will be noticed, deal essentially with gamma ray therapy. As already indicated, a certain amount of beta radiation is possible when a radium source is embedded in tissue. Since biological effects are almost certainly the result of ionization in tissue, and beta rays are ionizing agents, beta ray therapy cannot be overlooked. This is particularly true in connection with the use of the many artificial radioactive isotopes (discussed in Chapter XVII) which can be injected into the human body, either as tracers or for possible selective absorption by specific organs.

**173 Strength of a Radium Source** — When radium needles are used, the dose delivered to the region treated depends on several factors: (1) the time of application, (2) the distance of the source from the diseased tissue, (3) the amount of absorption by the materials enclosing the radium salt and by tissue, and (4) the total quantity of radium sealed in the tube, that is, on what we may call the strength of the source.

The strength of the source is expressed in milligrams of radium, and it is measured by direct comparison with a standard. In 1912 a tube containing 16.74 milligrams of radium in the form of radium chloride, prepared by Madame Curie, was adopted as an international standard by a Committee of the Congress of Radiology and Electricity. This is kept in the International Bureau of Weights and Measures at Sevre, near Paris. National secondary\* standards have been made by comparison with the international standard, and are in the possession of such institutions as the National Physical Laboratory in England, the Bureau of Standards in Washington, and the National Research Laboratories in Canada. When a radiologist buys a radium needle, its strength has been found by comparison with a National Standard and it should be accompanied by a certificate which reads like the following one:

*This certifies that the above described needle has been compared with the standards of the National Research Laboratories, and found to emit gamma radiation equivalent to x milligrams of radium in equilibrium with its disintegration products and contained in a Thuringian glass tube 0.27 mm. thick.*

Note that comparison between the specimen and the National Standard is made by using gamma rays only. This is readily done by using an electroscope with a lead wall of sufficient thickness to absorb completely all beta rays falling on it. The specimen to be measured and the standard are placed successively at the same distance from the electroscope, and in each case the rate of discharge measured. The two quantities of radium, as measured by gamma ray emission, are then in direct proportion to the rates of discharge, corrected in the usual way for natural leak.

The meaning of the phrase "in equilibrium with its disintegration products" is explained in section 177.

Alternative methods of stating the strength of a radioactive source will be found in section 178.

**174 Dose in Roentgens** — In gamma ray therapy, doses are now expressed in roentgens. Measurements by a number of different experimenters, using air-wall chambers, indicate that "for present medical purposes the quantity of gamma radiation received in one hour, at a distance of 1 cm. from a point source containing 1 milligram of radium element surrounded by

\* In addition to the important U. S. standard, a series of substandards have been recently prepared under the direction of the Committee on Standards of Radioactivity of the National Research Council of the United States. These standards have been or will be deposited at the Bureau of Standards in Washington and are to be used as working standards for investigators who may desire them.

0.5 mm platinum may be regarded as approximately equivalent to 8 roentgens (Proposals of British X-Ray and Radium Units Committee, 1937). 8.4 is probably a better mean value. If no correction is made for wall thickness, the number of 9 may be used to estimate the approximate dose. Stated otherwise, the above means that an estimate of the dose in  $r$  units, uncorrected for absorption or for finite size of needle or of number of needles in an applicator, may be made with fair accuracy, by the following relation

$$\text{Dose} = \frac{9 \times \text{milligrams of radium} \times \text{time in hours}}{(\text{distance in centimeters})^2} \text{ roentgens}$$

For example, for a 10 mg needle, used for 2 hours, the dose at 5 cm from the source is  $\frac{9 \times 10 \times 2}{25}$  or 7.2 roentgens. If the needle is surrounded by

0.5 mm of gold, by using the coefficient 0.14 for gold given in Table XXXI, we see that this dose when corrected for absorption by the gold, is  $(1 - 0.5 \times 0.14)$  or 93 per cent of 7.2.

For more accurate work, especially where a number of needles are combined in different arrangements to make applicators of different shapes, there are available dosage tables which a radiologist can consult.

Measurements at the Memorial Hospital, New York, indicate that the erythema dose resulting from gamma radiation corresponds to a mean value in the neighborhood of 1000 roentgens.

Before leaving this question of dosage, we again quote from the Recommendations of the 1937 International Congress of Radiology: "The specification of the conditions of gamma-ray treatments should, where possible, include statements of—

- I *Quantity* — The total quantity of radiation (expressed in roentgens) estimated to have been received by the lesion.
- II *Particulars of Radium Source* — (a) The total amount and nature of radioactive substance employed (expressed as equivalent mgm of radium element). (b) Type, number, and distribution of the containers. (c) The material and thickness of filters and the nature of the material externally adjacent to the skin.
- III *Technic* — (a) In the case of surface applicators, or "large radium units," the quantity of radiation per field at the surface. (b) The dosage rate during each individual irradiation. (c) The total time over which a course of treatments is spread. (d) The time intervals between successive irradiations. (e) In the case of surface applicators or large radium

units, the radium-skin distance (f) The number, dimensions, and situations of the ports of entry "

**175. Radon** — Suppose a radium salt is heated and the occluded gases collected and sealed in a tube, or, alternately that a solution of radium chloride dilute hydrochloric acid, which has stood for some time is boiled and at the gases driven off are collected. It is found, by testing with an electroscope, that the tube containing the gases is strongly radioactive. If measurements of the ionization are made every hour by a gamma-ray electroscope, it is noticed that at first the activity of the tube increases until, after some five hours, it has reached a maximum. Thereafter, if the tube is examined every 4 hours for a succession of days, it is found that its radioactivity steadily becomes less and less. The numbers given in Table XXXII show the rate at which the tube loses its radioactivity.

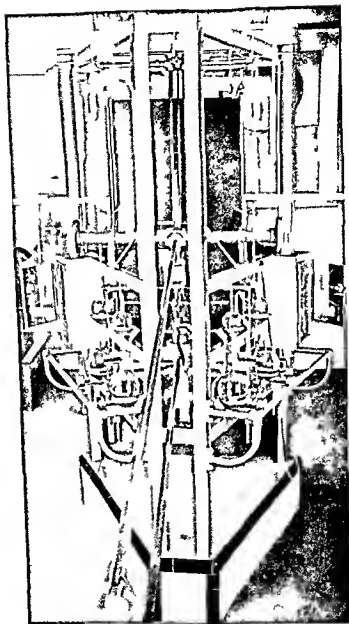
TABLE XXXII — DECAY OF ACTIVITY OF RADIIUM EMANATION

Time	Activity	Logarithm of Activity	Change in Log per Day
0	100	2.000	.078
1 day	83.5	1.922	.079
2	69.7	1.843	.078
3	58.2	1.765	.078
4	48.6	1.687	.079
5	40.6	1.608	.078
6	33.9	1.530	.078
7	28.3	1.452	.079
8	23.6	1.373	.079
9	19.7	1.295	.077
10	16.5	1.218	
20	2.7		
30	0.45		

It should be clear from this table that, although the gases collected from a radium salt or a radium solution, exhibit marked radioactivity, they differ in one important respect from the original radium preparation. When a needle containing a radium salt is tested day after day no change\* is detected, but, with the tube containing the gases, the numbers in Table XXXII show that *its activity at the end of a month has almost disappeared.*

In addition to the radioactive constituent in the tube, the gases collected contain hydrogen, oxygen, helium, and carbon dioxide. When these are removed by appropriate means, what is left is a radioactive gas, called *radium*

\* More accurately, at the end of 1 year, a loss of 4 parts in 10,000 can be detected



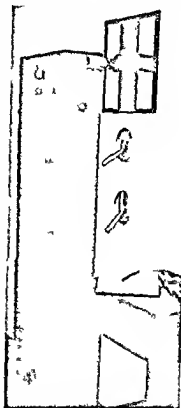
Courtesy G. Failla and Edith Quimby

FIG. 174. Semi-automatic control radon extraction apparatus designed by G. Failla (Memorial Hospital, New York) and installed by J. E. Rose (United States Marine Hospital, Baltimore).



*emanation or radon* From a gram of radium, only about three fifths of a cubic millimeter at atmospheric pressure, can be obtained. Radon has been shown to be an element of atomic weight 222, belonging to the family of the rare gases. Chemically, there is nothing remarkable about it, but in radiology it is of tremendous importance. With a suitable emanation plant, it is possible to keep a supply of radium, and without touching the original source, to seal the radon into glass tubes and use them instead of radium needles. Figures 174 and 175 are photographs of an emanation plant designed by G. Failla of the Memorial Hospital, New York, and installed by J. E. Rose, in the United States Marine Hospital, Baltimore.

To use a radon tube intelligently, it is necessary to be familiar with the law governing its loss of activity, that is, of what is called its *decay*. If we plot the results of Table XXXII, activity against time, we obtain the curve 1 shown in Fig. 176. Examination of this curve shows it to be exponential, that is, of exactly the same shape as that given in curve 1, Fig. 126. That figure, it will be recalled, illustrates the reduction in intensity of a homogeneous beam of x rays as a result of absorption. As already indicated in section 112, we can describe in three ways an exponential law. In terms of curve 1, in Fig. 176, showing the decay of radon, we may state (1) *Each day the activity decreases by 16.5 per cent of the activity of the preceding day.* Thus, if we decrease 83.5 by 16.5 per cent, we obtain 69.7. Or, if we decrease 69.7 by 16.5 per cent, we obtain 58.2. (2) In 3.82 days the activity has decreased one half. This time is the *half-period* of radon. (3) The curve is exponential, and therefore is described by the law  $I = I_0 e^{-\lambda t}$ , where  $I_0$  is the initial activity,  $t$  is the time, and  $\lambda$  is a coefficient. From this law it follows as already shown in section 112, that the logarithm of the activity decreases by



Courtesy G. Failla and Edith Quimby

FIG. 175 Control panel for radon apparatus shown in Fig. 174. The control room and the radon apparatus are separated by a two-foot concrete wall.

the same amount each day (or any time interval) This is shown by the numbers in the last column of Table XXXII

If we use logarithms, the exponential law may be written

$$\lambda = \frac{2.30 (\log_{10} I_0 - \log_{10} I)}{t}$$

For radon, this gives us

$$\lambda = \frac{2.30 \times 0.78}{1} = 0.18,$$

if the time is expressed in days

It is left as a problem for the student to prove that  $T$ , the half-period, that is, the time in which the activity falls by one half (from  $I_0$  to  $\frac{1}{2}I_0$ , for example) is connected with  $\lambda$  by the relation

$$T = \frac{0.69}{\lambda}.$$

For  $\lambda = 0.18$ , this gives 3.82 days for  $T$

**176 Growth of Radon** — Suppose from a supply of radium chloride kept in solution, all the radon is collected at various time intervals. It is found that, when the solution has been left untouched for a month or two, the radioactivity of the collected radon at the end of such an interval is just as great as when the solution is left untouched for six months, or a year, or two years, or any long period. On the other hand, if the radon is collected after intervals of 1 day, 2 days, 3 days, and so on, the activity is found to be

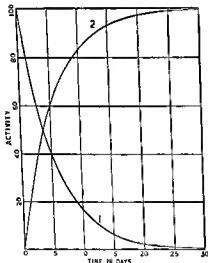


FIG 176 Graph 1 shows the decay of radium emanation graph 2 its growth

greater the longer the interval, until a maximum is reached after about one month. The numbers in Table XXXIII and curve 2 in Fig 176, show the exact rate at which the activity increases, maximum activity being assigned the value 100

The figures of Table XXXIII are readily interpreted in terms of two processes (1) The manufacture or growth of radon at a constant rate, and (2) its decay in accordance with the law already explained, namely, that each day the loss of activity of radon is 16.5 per cent of its activity the preceding

day. If we start with a quantity of radium salt initially free from radon, each day a certain amount of radon is manufactured, and at first the total amount steadily increases. But, as the total quantity increases, the amount decaying also increases, until ultimately a balance is reached when the loss in a day due to decay is exactly equal to the amount added.

TABLE XXXIII — GROWTH OF RADIUM EMANATION FROM RADIUM

Time Interval	Percentage of Maximum Value
1 day	16.5
2	30.3
3	41.8
4	51.4
5	59.4
10	85.5
20	97.3
30	99.5

A financial illustration may not be amiss. Suppose a man deposits in a bank \$16.50 every day, and, in addition, each day (after the first) before he makes his deposit withdraws 16.5 per cent of the amount to his credit. His account will increase in exactly the same way as the figures of Table XXXIII, but it will never exceed \$100.00. When that amount is reached, he takes out 16.5 per cent or \$16.50, and puts in exactly the same sum. Equilibrium has been obtained.

**177 The Curie and Millicurie.** — In much the same way, when radon accumulates in a vessel containing a radium salt, a fixed maximum balance or equilibrium amount is reached in a little over a month's time. If the quantity of radium is 1 gram, the equilibrium amount of radon is called 1 curie, or if 1 milligram of radium is available, the equilibrium amount is 1 millicurie (mc). In actual practice, provided the original quantity of radium is sufficient, it is not necessary to wait until equilibrium has been established. From the numbers given in Table XXXIII, it should be evident that from a 100 mg supply of radium, every day a tube containing 16.5 mc could be obtained. From a 1000 mg source 165 mc of radon are available every day. This can be subdivided among a number of tubes or seeds. For example, sixteen tubes each containing about 10 mc can be supplied every day by a center possessing 1 gram of radium and an emanation plant.

The use of radon tubes has the great advantage that the original radium supply is left untouched, with no danger of the loss which sometimes occurs when radium needles are used. Moreover, from a single center tubes with

an initial activity of the same order as that of small radium needles can be sent all over the country. On the other hand, in reckoning dosage, radon seeds have the disadvantage that correction must be made for the decay in activity. That, however, involves only a little arithmetic.

Although, strictly speaking, a curie is the amount of radon in equilibrium with one gram of radium, the practice of expressing strengths of radioactive sources in general in terms of this unit has become fairly common. Certain objections to this practice, as well as a suggested new unit, will be found in section 178.

**Disintegration and Nature's Transmutation**—If radium emanation disappears, and this seems to be the case, since it steadily loses its radioactivity, what becomes of it? As always, experiment helps provide the answer. When a metal wire, preferably negatively charged, is inserted in a tube containing radon, left for two or three hours, and then removed, it is found to be radioactive. Careful investigation shows that the wire is coated with an invisible layer of solid material to which the name *active deposit* is given. If the coated wire is tested by an electroscope at successive time intervals of about 10 minutes, it is observed that the activity steadily decreases.

Now what is the explanation of these changes? The story of the unraveling of these somewhat mysterious radioactive processes, one of the most fascinating in the history of physics, was first given by Rutherford working in collaboration with Soddy, about the beginning of this century. To understand it, the student is first asked to recall that an alpha particle has a mass of 4 on the atomic weight scale and a charge of 2 positive units. It is, therefore, an ionized atom of atomic weight 4 and atomic number 2, and these numbers strongly suggest the element helium. Evidence that an alpha particle is indeed a doubly ionized helium atom was found in the early days of the study of radioactivity. Helium was found occluded in radioactive ores, and in 1903 Ramsay and Soddy showed that it was present in radium emanation. But most striking of all was a direct experimental proof made in 1909 by Rutherford and Royds. Alpha rays from a radioactive source enclosed in a vessel were allowed to escape through an extremely thin glass window into a second vessel, where they were collected. By a spectrum test it was shown that helium was present in the second vessel in an amount which gradually increased with the number of alpha particles collected. This proved conclusively that alpha particles were nothing but the nuclei of helium atoms.

We may conclude, then, that the element radium shoots off atoms of helium. In considering where they come from, it is well to recall that the difference between the atomic weight of radium, 226, and that of radon, 222, is 4. The

conclusion that the alpha particle is ejected right out of the nucleus of a radium atom can scarcely be avoided. It is an example of the disintegration of an element which occurs spontaneously with radioactive materials, and it is this property which distinguishes a radioactive element from a nonradioactive one. The nuclei of the atoms of radioactive elements are unstable, those of ordinary elements stable. (In Chapter XVII, we shall see that it is possible to create unstable isotopes for many elements whose normal isotopes are stable.) Due to this instability, every now and then an explosion occurs, and a particle is ejected from the nucleus, leaving behind the nucleus of a new atom. This process, therefore, is a genuine example of the transmutation of one element into another. Radium, a metal belonging to the barium family, is transformed



FIG. 177 Schematic representation of transformations from radium to radium G or lead

by the ejection of alpha particles, into radon, a member of the rare gas group. Since the atomic number of radium is 88 and the alpha particle has an atomic number of 2, the atomic number of radon must be 86.

This transformation or transmutation from radium to radon is but one step in a whole series of successive changes, all of which have been carefully investigated. Atoms of radon are unstable, and when they explode, they also shoot off alpha particles leaving behind atoms of radium A. This is another radioactive substance, with a half period of three minutes. The process of disintegration continues and radium A, emitting alpha particles, is followed by a series of successive generations—radium B which changes to radium C by the emission of beta and gamma rays, radium C to C' by the emission of beta and gamma, and C' to D by the emission of alpha (or alternately C to C'' by the emission of alpha and C'' to D by emission of beta and gamma), D to E by the emission of beta and gamma, E to F by emission of beta and gamma, and finally F (polonium) to G by the emission of alpha. There the process stops because radium G is stable, being nothing but common lead.

This series of transformations is visualized by the diagrams of Fig. 177, and further details about half-periods are given in Table XXXIV.

In connection with Table XXXIV, the following things should be noted

(1) The half period of radium, 1600 years, is so long that the total loss, even in the course of a year, may be neglected \* For that reason, the number of atoms of radon manufactured each day by a given amount of radium is, for all practical purposes, constant

(2) Because of the long half-period of radium D, namely 22 years, it grows very slowly and hence, in a freshly prepared radium salt or tube of radon, the amounts of this product and of its posterity are extremely small The active deposit is a mixture of the products A, B, and C

TABLE XXXIV — RADIUM AND ITS PRODUCTS

Substance	Atomic Weight	Atomic Number	Half period	Emission
Radium	226	88	1600 years	alpha
Radon	222	86	3.82 days	alpha
Radium A	218	84	3.0 mins	alpha
Radium B	214	82	26.8 mins	beta, gamma
Radium C	214	83	19.7 mins	beta, gamma
Radium C*	214	84	$2 \times 10^{-4}$ sec	alpha
Radium D	210	82	22.2 years	beta, gamma
or				
Radium C	214	83	19.7 mins	alpha
Radium C*	210	81	1.32 mins	beta, gamma
Radium D	210	82	22.2 years	beta, gamma
Radium E	210	83	5 days	beta, gamma
Radium F	210	84	139.5 days	alpha
(polonium)				
Radium G	206	82	stable	
(lead)				

\* It will be noted that radium C can disintegrate by two different processes to form after two generations radium D. Of all the atoms of radium C which disintegrate 99.96 per cent give birth to radium C' and only 0.04 per cent to radium C.

(3) It will be noted that radium itself gives off alpha rays only, although at the beginning of this chapter it has been stated that a radium salt gives off alpha, beta, and gamma rays. There is no real contradiction, however, because if a radium salt is sealed in a tube, disintegration is going on constantly and there is present in the tube a mixture of all the products. From the information given in Table XXXIV, it will be seen that gamma rays are emitted by the products B and C. The emission from B is so weak and so feebly penetrating that for all practical purposes, radium C is the source of the gamma rays used in therapy.

We have stated above that, when radon is removed from a radium solution, maximum (gamma ray) activity is not reached for some five hours. This is

\* In two months the actual loss is about 0.007 per cent.

because it takes that length of time before the maximum amounts of radium B and C are obtained

(4) The end product, radium G, is stable, being in fact nothing but ordinary lead. In this connection, by means of a little elementary arithmetic, we can make a simple quantitative test. During the successive changes which take place in the transformation from radium to sterile lead, a total of five alpha particles and four beta are emitted. As far as the alpha particles are concerned, this represents a reduction in mass of  $5 \times 4$  or 20 units. Since the mass of a beta particle is so small, we can neglect any change in mass due to it, except for very special calculations. Therefore, since the atomic weight of radium is 226, the atomic weight of lead should be  $226 - 20$  or 206. Mass spectrograph data show that lead has an isotope of mass 206 in perfect agreement with this calculated value. But long before mass spectrograph data were obtained, H. N. Schmid in Vienna in 1914 measured chemically the atomic weight of lead obtained from pitchblende and the value he obtained was 206.05\*.

By the use of atomic numbers, another numerical test may be applied to radioactive transformations. Since an alpha particle has a charge of 2 positive units, a loss of 5 particles means a reduction in the total positive charge of 10 units. A beta particle, however, has a unit negative charge, and hence the loss of 4 beta rays means a decrease in total negative charge of 4 units or a gain of 4 positive units. The net result, therefore, of the loss of 5 alpha and 4 beta particles is a loss of  $10 - 4$  or 6 positive units. Since the atomic number of radium is 88, it follows that the atomic number of lead should be  $88 - 6$  or 82, as in fact it is.

(5) A glance at Table XXXIV shows that radium B, radium D, and radium G or lead have the same atomic number 82. Chemically therefore, these substances have the same properties, since the outer electronic system in an atom of each must be the same. Their atomic weights, however, are 214, 210, and 206. They are, therefore, radioactive isotopes of one and the same element. As a matter of fact, we owe the name isotopes to Soddy, the co-worker of Rutherford in the pioneer work on disintegration, because it was this work which first revealed their existence.

178 The RHM and the Rutherford—E. V. Condon and L. F. Curtis of the National Bureau of Standards have suggested the adoption of two new units of radioactivity

(a) To measure the intensity of strength of a source, as far as gamma

\* The student will recall that the ordinary (chemical) atomic weight for lead is 207.2. This is because it is a mixture of several isotopes.

radiation is concerned, the unit suggested is the r h m. (pronounced rum). By definition 1 r h m is the strength of a source of gamma radiation which produces a dose of 1 roentgen in 1 hour at a distance of 1 meter from the source

If we recall that the dose at a distance of 1 cm from 1 mg of radium in 1 hour is equal to 8.4 roentgens, we see that the dose from 1 gram of radium in 1 hour at a distance of 1 meter

$$= \frac{8.4 \times 1000}{100^2} \\ = 0.84 \text{ roentgen,}$$

since 1 gram = 1000 mg, and 1 meter = 100 cm.

Therefore, to obtain a dose of 1 roentgen in 1 hour at a distance of 1 meter, we should need 1/0.84 or 1.19 gm of radium. Hence 1.19 gm radium (or 1.19 curie of radon) has a gamma ray strength of 1 r h m.

The author of this book can see no great advantage in using this new unit rather than to continue specifying the gamma intensity of any radioactive source as the gamma ray equivalent of so many grams or milligrams of radium. Admittedly, however, the r h m unit is independent of any radioactive substance and in that respect is fundamental.

(b) When a series of radioactive products, like radium and its successive generations, are in equilibrium, the following facts are of importance:

(i) The relative equilibrium amounts of any two products are directly proportional to their half-periods. The amount of radium A, for example, with its half period of 3 minutes, is many times less than the amount of radium D with its half period of 22.2 years.

(ii) When equilibrium has been attained, the actual number of atoms which disintegrate each second is the same for all products. This follows at once since, when a product has its equilibrium amount, it must gain as many atoms as a result of disintegration of its parent substance as it loses because of its own disintegration. Hence the number of disintegrating atoms per second is an important number which can be used to describe the strength of a source. For that reason, Condon and Curtiss have suggested the adoption of a new unit, the *rutherford*, for describing the strength of any radioactive source, not, be it noted, its gamma ray strength.

By definition, 1 rutherford, or 1 rd, is the strength of a radioactive source for which the number of disintegrating atoms per second is  $10^6$ , or 1 million. Hence, 1 micro rutherford or 1 micro rd, corresponds to 1 disintegration per second.

By the use of counters, it has been found that in the radium family, the



number of disintegrating atoms per 1 gram of radium per second is equal to  $3.7 \times 10^{10}$ . Hence 1 gram of radium has a strength of  $3.7 \times 10^4$  rd. Since 1 curie is the amount of radon in equilibrium with 1 gram of radium, it follows that, if the curie is used as a general unit for estimating the strength of any radioactive source, 1 curie corresponds to  $3.7 \times 10^4$  rd.

Obviously, by the use of the rutherford, there is no need whatever to use the curie as a general unit for the strength of radioactive materials. On the other hand, there is really no great objection to continuing to use it in the more general sense as long as it is clearly understood that it then corresponds to  $3.7 \times 10^{10}$  disintegrations per second.

**179. Artificial Transmutation** — The whole story of disintegration shows that nuclei of radioactive atoms are complex and unstable and strongly suggests the complexity of stable atoms. If this is true, it is possible that a direct hit by a heavy particle like an alpha ray might smash the nucleus of an atom into its constituents. Breaking up the atom in this way must not be confused with releasing some of the electrons surrounding the nucleus. The removal of one or more of these extranuclear electrons does not destroy the atom, for subsequently other electrons are attracted by the ion and the atom returns to its normal state. Breaking up the nucleus is a different matter. It means a complete destruction of the atom, and for two reasons it is a very difficult thing to do. In the first place, it requires an enormous amount of energy, and in the second place, the nucleus must be hit "head on." In some cases an alpha particle moving at high speed has the necessary amount of energy, but the chance of it making a direct hit is extremely slight. As the nucleus occupies about as much space in an atom as a fly in a cathedral, the vast majority of bombarding alpha particles pass right through the atom leaving it intact, except for the occasional removal of an outside electron.

Sometimes the approach to the nucleus is so near that the alpha ray is deflected to one side, and, at the same time, the struck atom—or, more accurately, its nucleus—has energy communicated to it and moves off to the other side. Figure 178, a cloud-track photograph taken when alpha rays



Courtesy N. Feather and the Royal Society

**FIG. 178** Scattering collision of an alpha particle with the nucleus of a helium atom. The alpha ray travelling along the path marked a strikes a helium nucleus and is deflected to travel along one arm of the fork while the struck nucleus moves off along the other arm.

were bombarding ordinary helium, provides an excellent example of this. It will be noted that the tracks are straight lines for all but one of the particles. As the photograph clearly shows, the single exception is marked by a forked track, one prong of which corresponds to the deflected path of the original alpha ray, the other to the path of the struck helium nucleus.

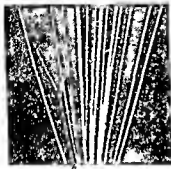
Occasionally the bombarding particle strikes head-on, and the struck nucleus, if light as hydrogen, is shot ahead with high speed. In one of the early experi-

ments, for example, alpha rays bombarded hydrogen, and the protons which had been hit in this way, were observed to cause scintillations on a screen placed far beyond the range of the original alpha particle.

And sometimes the alpha particle enters right into or coalesces with the bombarded nucleus, forming a new unstable atom which disintegrates. A transmutation is then the result. In 1919 Rutherford bombarded the gas nitrogen with alpha rays and obtained hydrogen because of such a process. This is then an example of what we shall call artificial transmutation, to distinguish it from the spontaneous natural transmutation of radioactive materials. The amount of hydrogen manufactured was too small to be detected by chemical means, but the most rigid tests showed that the effect was none the less real. There was no doubt about it. Protons or hydrogen nuclei were

knocked out of nitrogen nuclei. The process of obtaining hydrogen in this way was not very economical, for a million alpha particles had to be fired to give one direct hit, and so to form one atom of hydrogen. But it was not the quantity of hydrogen evolved that mattered, rather the fact that a direct proof had been given that protons existed in the nuclei of nitrogen atoms. Within a few years it was shown that protons could be knocked out of many other atoms as well, and the view that all nuclei are composed of electrons and protons became widely held. In the light of subsequent work, some of which will be given in Chapter XVI this view had to be altered.

Later we shall show that when an alpha particle interacts with a nitrogen nucleus with the emission of a proton, an oxygen atom is also formed. A cloud track photograph of this transformation, taken a number of years after Rutherford's classic experiment, is shown in Fig. 179. In this photograph note



Courtesy P. M. S. Balke and the Royal Society

FIG. 179 Disintegration collision of an alpha particle with a nitrogen atom. The alpha particle travelling along the path marked *b* collides with a nitrogen nucleus and is captured. A disintegration results: the left hand long thin arm of the fork marking the path of an ejected proton; the right hand short fat arm the path of an ejected oxygen atom.

the fork at the end of one of the alpha ray tracks. The long, thin "streak" forming one arm of the fork, corresponds to the proton path, the much shorter and somewhat irregular second arm, to the track of the oxygen atom.

**180 Protection** — As with x-rays, so with radium, it is highly important to protect from possible serious injury all who work with radium in any capacity. If a radium preparation is carelessly handled, beta rays may injure the hands to such an extent that cancer ultimately develops. "Ten milligrams of radium, or ten millicuries of radon, in a small tube thin enough to permit the escape of most of the beta-rays, at a distance of 3 mm from the skin, will deliver enough radiation to produce a sharp reaction in 10 minutes exposure" (Quimby). For that reason, to quote from the 1937 International Recommendations, "the radium should be manipulated with long handled forceps, and should be carried from place to place in long handled boxes, lined on all sides with at least one centimeter of lead."

Gamma rays may also have important injurious general effects, and an adequate thickness of a protective material like lead should be used. Moreover, care should be exercised that a worker is shielded not only from the direct beam, but from scattered rays as well.

There are dangers from even extremely small amounts of radioactive material unless rigid precautions are taken. For example, in the past, radium poisoning has occurred among industrial workers engaged in radium dial painting. In an excellent article\* by Robley D. Evans of the Massachusetts Institute of Technology, attention is directed to a case of radium poisoning, in which "no clinical symptoms were observed until eight years after the termination of a five-year exposure as a radium dial painter." The danger of such cases occurring at the present time is slight because of rigid hygienic and other measures which are observed, but dangers are ever present wherever personnel are handling radioactive materials, and precautions cannot be too rigid.

In an appendix the recommendations for x-ray and radium protection are given.

**181. Other Radioactive Families** — In Table XXXIV we have listed the various members of the radium family. These, however, are by no means the only radioactive substances which occur in Nature. Radium itself is a descendant through several generations of uranium I, a radioactive element of atomic number 92, atomic weight 238, with a half period somewhat less

\* "Protection of Radium Dial Workers and Radiologists from Injury by Radium"  
Journal of Industrial Hygiene and Toxicology Vol 35, Sept 1943

than  $5 \times 10^8$  years. Uranium II, the 234 isotope, with half-period  $2.7 \times 10^5$  years, occurs in this same family. Both these isotopes of uranium emit alpha rays. The third isotope, the 235 variety, occurs in another family called the actinium series, and is also an alpha ray emitter with a half-period of  $7 \times 10^8$  years. The half-periods of all three isotopes of uranium are so extremely long that for many purposes, this element may be considered stable.

A third family consists of thorium products.

One of the members of this family is mesothorium, a substance which with an atomic number of 88, is an isotope of radium. For that reason, if radium and mesothorium are present in the ore from which radium is extracted, it is not possible to separate them by ordinary chemical means, and sometimes radium salts contain mesothorium as an impurity. This is not desirable, because, although mesothorium emits gamma rays, its activity decreases about 10 per cent in a year, unlike radium which, as we have seen, remains sensibly constant.

### PROBLEMS AND QUESTIONS

- 1 Explain the meaning of "millicurie of radium emanation"
- 2 What radiations are given off from a tube of radium emanation enclosed in a tube of platinum 0.5 mm thick?
- 3 If at a certain time you were provided with 100 millicuries of radium emanation, how much would you have after 48 hours? *Ans* 69.7 mc
- 4 A radium emanation tube sent from New York to Kingston had a strength of 100 millicuries when it left New York. (i) What is its strength when used in Kingston for treatment 48 hours later? (ii) After what time will its strength be 50 millicuries? (iii) After what approximate time will a 10 milligram tube of radium salt fall to half value? *Ans* (i) 69.7 mc (ii) 3.82 days (iii) 1600 years
- 5 The same type of curve is obtained when the decrease in the activity of radon is plotted against time as when the decrease in the intensity of a homogeneous beam of x rays is plotted against the thickness of an absorbing layer of matter. Indicate the general nature of this curve, explaining the law which defines it.
- 6 On a certain day a radium emanation tube causes the leaf of an electroscope to fall at the rate of 60 divisions per minute. How fast will the same tube (at the same place) cause the leaf to fall (i) after 24 hours, (ii) after 48 hours? *Ans* (i) 50.1 (ii) 41.8
- 7 If all the radon is collected every second day from 1 gram of radium, find the strength in millicuries of the amount collected, on the day collection is made. *Ans* 303 mc
- 8 One tenth gram of radium is left standing in solution for at least a month. The accumulated radium emanation is then drawn off each day for three successive days, and each day sealed in a single tube. Find the strength of the three tubes on the third day. *Ans* 69.7 mc, 16.5 mc, 13.8 mc
- 9 If a gram of radium was the total amount in an emanation plant, what is the maximum number of 20 millicurie tubes which could be obtained from this plant at one time? (i) About how long would it be necessary to wait before collecting the emanation

to obtain this maximum number? (ii) What would be the strength of one of the 20 mc tubes 24 hours after it was removed from the plant?

10 A radium emanation plant, with 1 gram of radium in solution, has all the active gas removed on a certain day. Work out how many millicuries could be taken from the plant on the next removal which takes place after an interval of three days. *Ans* 418 mc

11 Radium D has an atomic number of 82 and an atomic weight of 210. On emitting beta and gamma rays it changes into radium E, which in its turn also emits beta and gamma rays, changing into polonium. Finally polonium emits alpha rays, changing into lead. Show that lead and radium D are isotopes and find, from the above data, the atomic weight of lead.

12 The atomic weight of radium is 226, and its atomic number is 88. If the final stable product after the successive transformations of radium is lead, of atomic weight 206 and atomic number 82, find the total number of (i) alpha particles emitted, (ii) beta particles, by the time a single radium atom has turned into an atom of lead.

13 (a) A radioactive substance A of atomic number 92 changes into B of atomic number 84 after a series of successive transformations. If in the process a total of 7 alpha rays are emitted, find the total number of beta rays emitted.

14 Radon is drawn off regularly every second day from an emanation plant containing 500 mg of radium in solution. Find the maximum amount (in millicuries) of radon which the plant can distribute every second day.

15 A small tumor is treated for 50 hours with gamma rays by 20 mg of radium in a needle. If the tumor is at an average distance of 3 cm from the needle, estimate the dose in roentgens, without correction for absorption. *Ans* 1000r

16 If radon is collected every day in an emanation plant containing 2 grams of radium, what is the maximum number of millicuries obtained each day?

17 A radioactive material decays according to a simple exponential law. If in 1 minute its radioactivity decreased by 10 per cent, find its half period by plotting a graph, or in any way you like. *Ans* 6.5 mins

## CHAPTER XV

### PRODUCTION OF HIGH VOLTAGE PART II

#### SUPERVOLTAGE TUBES AND HIGH SPEED PARTICLES

**182 Importance of Supervoltage** — During the last decade, the construction of supervoltage machines has played an important part in the development of radiology physics. In Chapter II only a passing reference was made to this work, because it was considered advisable to defer the discussion until the reasons for using supervoltages could be made clear. Let us now examine some of them.

(1) From the relation

$$\text{shortest wave length} = \frac{12,395}{\text{maximum voltage}},$$

we see at once that the higher the voltage across a tube, the shorter the minimum wave length in the continuous x-ray spectrum. With a million volts, for example, the shortest wave length is about 0.012 angstrom. The wave length of maximum intensity in the continuous spectrum is, of course, somewhat longer than this.

Obviously, then, by using supervoltages, extremely penetrating beams of rays can be obtained. Now there is some evidence, although it is by no means conclusive, that extremely short wave lengths are preferable to longer ones for biological reasons. In any case it is desirable to examine carefully the effects of as wide a range of wave lengths as can be obtained.

Moreover, the more penetrating the x-ray beam, the greater the percentage depth dose, that is, the greater the percentage of the surface dose delivered to deep seated tissue. (See again, section 160.)

(2) The intensity of a beam of x rays increases steadily with increasing tube voltage, hence ultrahigh intensities may be obtained with supervoltage machines.

(3) With sufficiently high voltages (about  $10^6$  million), wave lengths comparable with those of gamma rays from radium C may be obtained. Already it has been demonstrated that x-rays, the equivalent of nature's gamma rays, can be obtained from a single tube, with intensity comparable with that of a radium source of 1000 grams.

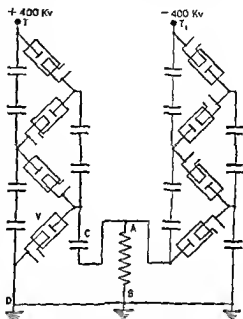
(4) By means of supervoltages extremely high speed cathode and positive rays can be obtained. With such particles transmutation experiments can be carried out with results of great importance in the field of radiology. For example, we shall see in the next chapter that by such means artificial radioactive materials can be manufactured.

The fact that million volt x-ray outfits are in operation in such centers as the Memorial Hospital, New York, the Huntington Memorial, Boston, and St. Bartholomew's Hospital, London, is ample evidence of the importance of supervoltage in radiology.

A number of different methods have been used for the development of supervoltages. Some of them are simple in principle, some are engineering jobs on a large scale. In the following sections we shall examine briefly the main features of the more important methods.

### 183 The Induction Coil

—Some years ago the General Electric constructed a special induction coil which could be run continuously at 700 000 volts. This was used for two or three years at the Memorial Hospital, but interrupter troubles create difficulties in connection with induction coils, and it is not likely that much use will ever be made of them for supervoltage work.

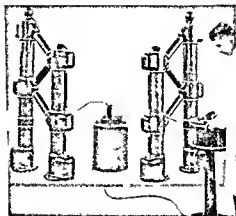


Courtesy Philips Gloeilampenfabrieken

FIG 180 The arrangement of rectifying valves and condensers in a cascade generator

**184 The Cascade Generator** — In this type, as developed by the Philips' Laboratories and the General Electric Corporation use is made of a combination of condenser and rectifying valve units similar to those used in the Villard and Greinacher rectifying circuits (Sections 79 and 80). An arrangement utilized in a Philips' generator of this sort, capable of developing 800 000 volts, is shown in the diagram of Fig 180. In this figure it will be noted that the circuit  $BAC_1V,D$  is similar to the Villard circuit of Fig 91,

except that only one rectifying valve and one condenser is used. By adding successive condenser-valve units in the manner shown in the figure, the original E M F developed in the secondary  $AB$  of the high tension transformer may be so multiplied, that terminal  $T$  is raised to a high positive potential,  $T_1$  to an equally high negative. In the generator represented in this figure, with a transformer voltage of only 100,000 volts  $T$  becomes  $+400,000$  volts,  $T_1 - 400,000$  volts hence between the terminals there is a P D of 800,000 volts. The photograph reproduced in Fig 181 shows the actual appearance of this generator or one similar to it, whose total height is some 8 feet



*Courtesy Philips Gloeilampenfabrieken*

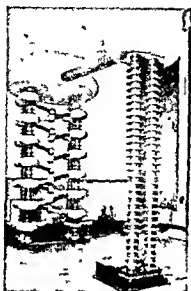
FIG 181 Photograph of a cascade generator

Making use of the same principle, the Philips' Company constructed a much larger generator for the Cavendish Laboratory, Cambridge, England. This machine, which has a total height of about 17 feet, develops 1,250,000 volts, although only 120,000 volts is necessary in the secondary of the transformer. Figure 182 shows the actual appearance of this generator. In this figure the generator proper with its zig-zagging valves is seen on the left. The double column on the right contains an extremely high resistance which is used in the measurement of the actual voltage developed by the method described in sections 27 and 186. The horizontal piece at the top of the photograph is a damping resistance by means of which electrical connection is made to the top of the measuring resistance (as shown) and to the x ray tube (not shown).

Figure 183 is a photograph of the negative end of a 4,000,000 volt generator used in the Philips' Laboratory at Eindhoven, Holland. An added feature in this photograph is the huge sphere gap, used for taking voltage measurements (see section 23).

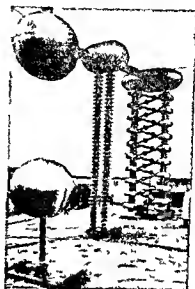


In all supervoltage generators *ample room* must be left between the high tension terminals and the ceiling or other grounded places, otherwise "flash-overs" will take place



Courtesy Philips Gloeilampenfabriek

FIG 182 A 1,250,000 volt cascade generator



Courtesy Philips Gloeilampenfabriek

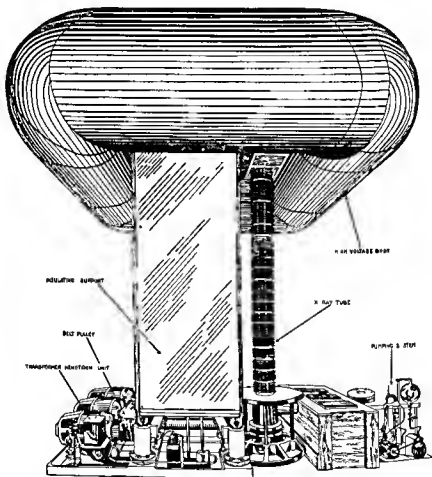
FIG 183 The negative end of a 4,000,000 volt cascade generator

**185 Van de Graaff Electrostatic Generator.**— A generator much simpler in principle than the cascade type and much cheaper to construct has been developed during the last decade. The first machine of this type was the invention of Van de Graaff, who made use of fundamental ideas discussed in elementary classes in electrostatics.

The student is asked to recall two of these: (1) An electric charge given to a hollow conductor goes to the outer surface, the potential at all points within such a conductor being the same. (2) An insulated charged conductor loses its charge if a pointed conductor is in contact with it, or, conversely, an uncharged insulated conductor, with a sharp point attached to it, will pick off a charge from a charged body placed near the point. In the first case, we sometimes state that the charge "slips off" the point. Actually, the charge accumulates on the point to such an extent that the resulting electric field in the air near the point is great enough to ionize the air. If the point is negatively charged, positive ions move towards it and annul its charge, thus leaving

negative ions in the surrounding region. Similarly, before a point picks off a charge, there is ionization between it and the neighboring charged body.

To understand the way in which these ideas are utilized in the Van de Graaff generator, a brief description is given of a comparatively small machine,



*Courtesy J G Trump*

FIG 184 A Van de Graaff generator capable of developing 1,000,000 volts or more

designed by J G Trump and R J Van de Graaff, of the Massachusetts Institute of Technology. The general appearance of one generator of this kind, capable of developing a million volts or more, is shown in Fig 184. The important details of the construction of a 500,000 volt generator may be

understood by reference to Fig. 185. An electric charge is accumulated on a hollow, insulated conductor C, some thirty inches in diameter, and twelve inches high, which stands on the top of an insulating column over three feet long and twelve inches in diameter. The column rests on a supporting base in contact with ground.

Within the base, there is a small transformer-rectifier unit so arranged that a negative charge slips off a row of points, one of which is represented by *a* in the diagram. These points are about one quarter inch from a grounded pulley revolved by a motor also housed within the base. A three-ply rubber fabric, making an endless belt about ten inches wide, passes around this pulley and a second insulated pulley, placed inside the insulated conductor at the top of the generator. When the machine is in operation, the motor keeps the belt moving at the rate of 5000 ft. per minute. A collector rod with points at *b* and at *c* is attached to the upper insulated pulley.

The action of the generator is somewhat as follows. As the left-hand side of the belt goes up with its negative charge, negative electricity is picked off at *b*. Most of this slips off at *c* going to the outside of the terminal, but some goes to the insulated pulley. Since this is situated inside a hollow conductor normally its potential would be the same as that of the conductor, but when a free charge of the same kind is thus added to it, its (negative) potential becomes higher than that of the terminal conductor. Hence, when a row of pointed conductors is attached to the inside of the terminal, as represented at *d*, the higher negative potential of the pulley causes an escape of positive electricity from these points. This escape of positive (1) still further increases the negative charge on the terminal, (2) annuls any negative left on the uprising belt, and (3) puts a positive charge on the downward belt. At the bottom of its downward path, the positive is annulled by the spraying action of the dis-

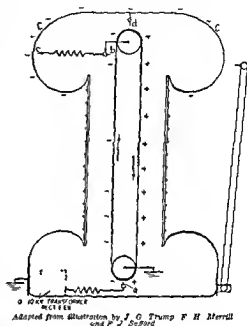
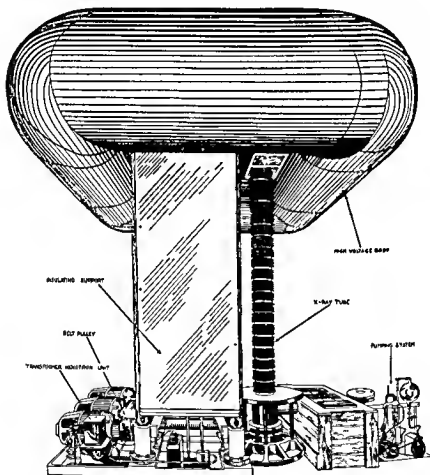


FIG. 185 Outline diagram of small Van de Graaff generator

negative ions in the surrounding region. Similarly, before a point picks off a charge, there is ionization between it and the neighboring charged body.

To understand the way in which these ideas are utilized in the Van de Graaff generator, a brief description is given of a comparatively small machine,



*Courtesy J G Trump*

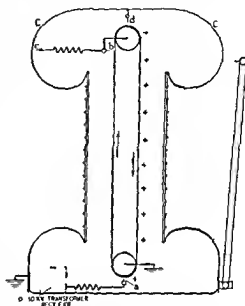
FIG 184 A Van de Graaff generator capable of developing 1,000,000 volts or more.

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Within the base, there is a small transformer-rectifier unit so arranged that a negative charge slips off a row of points, one of which is represented by *a* in the diagram. These points are about one quarter inch from a grounded pulley revolved by a motor also housed within the base. A three-ply rubber fabric, making an endless belt about ten inches wide, passes around this pulley and a second insulated pulley, placed inside the insulated conductor at the top of the generator. When the machine is in operation, the motor keeps the belt moving at the rate of 5000 ft per minute. A collector rod with points at *b* and at *c* is attached to the upper insulated pulley.

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Adapted from illustration by J. O. Trapp & H. Merrill and P. J. Safford

FIG. 185 Outline diagram of small Van de Graaff generator

voltage of about a million and a half volts, then causes a current of about 1 ma through this resistance. By means of an electrostatic voltmeter, with a range up to 1500 volts, the potential difference across 1/1000 of the resistance is read directly off this instrument placed on the control panel of the machine.

(4) *Generating Voltmeter* — An entirely different method which is being successfully used for supervoltages, makes use of a simple fundamental idea. The student will recall that, when an *uncharged* insulated conductor, such as *BC*, Fig 186, is placed in the electric field near a *charged* conductor such as *A*, induced charges appear at the opposite ends of the uncharged conductor. If

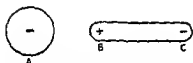


FIG 186 Induced charges of opposite sign appear at the ends of an uncharged conductor placed in the field of a charged conductor

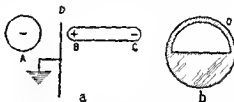


FIG 187 A to-and-fro movement of charges takes place in the conductor *BC* when the disc *D* is rotated

*A* has a negative charge, the induced charge at the near end *B* is positive, at the far end, negative. (If the conductor *BC* is grounded, the end *B* will still be positive, and negative will go to earth.)

Now suppose that a grounded metallic disc *D*, cut as shown in Fig 187*b*, so that nearly one half is removed, is placed between the conductors *A* and *BC*, as shown in Fig 187*a*, and rapidly revolved. It should be evident that, when the open part of the disc is opposite the end *B*, the conductor *BC* is under the influence of the charge on *A* and so induced charges appear as before. But, when the uncut half of the grounded disc is in front of *B*, *BC* is shielded from the field of *A*, and hence during that interval this conductor returns to its normal state. Since the disc is in rapid revolution, it follows that there will be a surging to and fro of electric charges, that is, an alternating current whose frequency is controlled by the speed of the disc. Moreover, the greater the potential of *A*, the greater the intensity of the electric field causing the movement of the charges, and the greater the magnitude of this alternating current. Hence, if we can measure the strength of this current, we are provided with a means of measuring also the potential of *A*.

In *generating voltmeters* this principle has been utilized as a satisfactory means of measuring supervoltages. As an example of the way in which the

principle is applied, a brief description is given of the essential features of an instrument of this kind recently described by Trump, Safford, and Van de Graaff, and used by them for the measurement of voltages, as high as a million and a half, generated by their high pressure electrostatic generator. Suppose the end  $C$  of the conductor  $BC$  is joined, as illustrated in Fig 188, to a point between the plate and the filament of two rectifying valves. (Actually a double diode valve is all that is necessary.) Then, when  $B$  is not shielded and  $A$  is negative, electrons flow from the end  $B$  through the valve

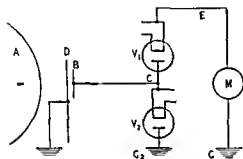


FIG 188 When the disc  $D$  is rapidly revolved an intermittent but unidirectional current flows through the microammeter  $M$

$V_2$  to ground at  $G_2$ , leaving the end  $B$  positive. When  $B$  is shielded, electrons cannot cross valve  $V_2$  to annul the positive charge, but they can cross valve  $V_1$ , flowing from ground at  $G_1$ , through  $M$ , a current-measuring instrument such as a microammeter. Through this instrument, therefore, there is an intermittent, but unidirectional current which, if the disc  $D$  revolves quickly enough, is recorded as having an average mean value.

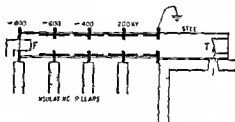
The arrangement actually used is not quite so simple as that shown in Fig 188. Since theory shows that the current through the microammeter is proportional to the frequency of the rotating disc, this is made with four sectors, equal in area and equally spaced (not unlike a Maltese cross) and the end  $B$  directly behind the disc, consists of eight brass sectors mounted on a Textolite ring. Alternate sectors (not  $B$ ) are electrically joined to form two sets of four each, and each set is joined to a separate double diode tube. In this way one set of four is shielded when the other set is not, and by a simple extension of the means illustrated in Fig 188, "substantially constant rectified current flows in the microammeter circuit." In the actual instrument, the connection similar to  $E$  of Fig 188 is a long shielded conductor and the microammeter is mounted on a panel fifty feet from the electrostatic generator. The scale is calibrated, and supervoltage read directly from the instrument.

**187. Supervoltage Tubes** — The problem of building tubes capable of operation on voltages of a million or more presents many difficulties. The insulation must be so good that there is no danger of spark over on the outside of the tube itself. Care must be exercised to guard against a discharge in the tube even with a cold filament, because once an electric field reaches a certain

value electrons can be pulled out of a cold metal. A good vacuum must be maintained in a tube, frequently of such large dimensions that vacuum pumps have to be in continuous use. Then, too, there are the added precautions necessary to protect both operator and patient from the dangers of electrical shock and from powerful beams of very penetrating rays.

The different ways in which these and other difficulties have been overcome will be understood from the following brief description of a few representative supervoltage tubes.

The General Electric Company has constructed, along more or less standard lines, a sealed-off tube, some five feet long, which is capable of operation on 400,000 volts. In this tube, by placing the target near the inner end of a long hollow copper cylinder, electrons are prevented from bouncing off the target and charging the inner surface of the walls of the tube, one of the common causes of tube puncture. The envelope itself, one quarter of an inch thick, is made of borosilicate glass, a material with high dielectric strength.



Adapted from illustration in the British Journal of Radiology

FIG 189 An 800,000 volt x ray tube of the multisection type

For much higher voltages, this firm has constructed multisection tubes, that is, tubes consisting of a number of glass cylinders separated by metal rings. Since the metal used is an alloy with the same coefficient of expansion as the glass, vacuum tight seals can be made. The metal rings are attached to electrodes extending inside the tube. By the use of these intermediate electrodes the total voltage between the filament and the target is subdivided, and, "the metal cylinders exert a focussing action on the electron beam and protect the glass from bombardment." (Read)

Figure 189, adapted from an illustration in an article by J. Read in the British Journal of Radiology, represents a large 800,000 volt tube of the multisection type built by the General Electric Company for the Swedish Hospital, Seattle. It will be noticed that the voltage across each section is only 200,000, and that the target is at ground potential. The whole tube lies outside the treatment room which is heavily insulated against penetrating rays except for the window through which they pass to the patient.

Another General Electric tube of the multisection type consists of ten sections, is 28 ft. 6 in. long, and is able to carry 10 ma. at 1,400,000 volts.

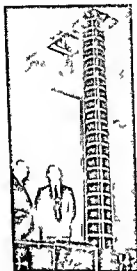
In most of the supervoltage tubes, the necessary low pressure has to be



maintained by the continuous operation of exhaust pumps. The Philips' Company, however, have utilized successfully the multisection principle in the construction of sealed-off tubes capable of withstanding supervoltages. In the Philips tubes each unit has glass ends of the re-entrant type, somewhat as used in the ordinary metal tube, Fig. 60, and the units are connected by soldering external metal pieces at adjacent ends after each unit has been separately evacuated. Connection between the units is subsequently made by

the electron beam itself, which perforates thin pieces of metal foil covering the central parts of the metal electrodes. A two unit tube of this type has been constructed capable of operation on 700,000 volts, and a three-unit tube, 6½ feet long, is capable of continuous operation with 1 or 2 ma, at 1,000,000 volts.

A million volt tube of an entirely different construction, developed at the Massachusetts Institute of Technology in connection with an electrostatic generator, is in use at the Huntington Memorial Hospital of the Harvard Medical School. The general appearance of this tube is shown in Fig. 190 (See also Fig. 184.) Insulation is provided by using a ten foot column of twenty porcelain sections resting on a grounded steel flange at floor level. Below the flange, a steel cylinder which forms the lower end of the x-ray tube, continues into the treatment room, as shown in Fig. 191. Electrons from a filament at the top of the tube are guided down the tube by electrostatic lenses, placed between each porcelain sector, until they strike the water-



Courtesy J. G. Trump

Fig. 190 The million volt x-ray tube in the Huntington Memorial Hospital of the Harvard Medical School

cooled lead target sixteen feet below. 'The target consists of a copper cup on the inside of which a 15 mil lead coating has been electroplated, the cup being cooled by a water jacket. The target is at ground potential but insulated from the tube extension, so that the current to the target can be read on a milliammeter at the control panel. The x-rays utilized in treatment are those transmitted downward through the target and water-cooling jacket' (Trump and Van de Graaff.)

By way of contrast to this tube, a brief reference is made to one made by Metropolitan Vickers for use in the Mozelle Sasson High Voltage X-Ray Therapy Department, at St. Bartholomew's Hospital, London. This tube thirty feet long and weighing ten tons extends horizontally through three

rooms. In the first room a generator can maintain the cathode at a negative potential of 500,000 volts or more. The central part of the tube, a grounded steel cylinder containing the water-cooled gold target, lies in the middle of the treatment room. Since in the third room a second generator can maintain the anode at a positive potential of 500,000 volts, potentials of at least 1,000,000 can be applied to the tube. The anode and cathode ends are separated from the middle portion by porcelain insulators, each five feet long, and elaborate precautions are taken to provide adequate protection from the rays. In this connection we quote from a booklet describing this installation: "The position within the treatment room, that is, the central twelve feet, is surrounded by a protective sheath, consisting of a six-inch layer of close-packed lead shot, enclosed between two coaxial steel cylinders. An aperture in this sheath allows the transmission of the x-ray beam. The protective sheath in its turn is surrounded by a steel cylinder which carries the filters, diaphragms, and applicators for defining the x-ray beam. The protective sheath and applicator cylinder can be rotated independently of each other. In this way it is possible to direct the beam of x-rays at will, either through the applicator towards the patient or into an absorbing lead saddle, six inches thick, suspended immediately above the tube. Thus, the portion of the x-ray tube within the treatment room is both shock proof and ray-proof."



Courtesy J. O. Trump

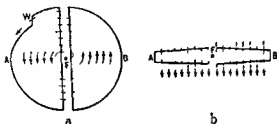
FIG 191 The lower end of the million volt x-ray tube shown in FIG 190

### 188 High Speed Particles The Cyclotron —

In section 179 it was shown that by bombarding nitrogen with alpha particles, both hydrogen and oxygen can be manufactured. The process is not very efficient because a direct hit between the nucleus of a nitrogen atom and the bombarding alpha particle must take place and the chances of this are only about one in a million. The results of this and similar bombarding experiments are so important, how-

ever, both in physics and in radiology, that ways and means have been sought of supplementing the limited supply of alpha particles by other high speed projectiles. This can be done in two important ways.

(1) By speeding up positive ions with supervoltages. As we have already emphasized, the greater the potential difference through which a charged particle falls the greater the kinetic energy which it acquires. The high voltage generators we have been describing, therefore, are sometimes used to accelerate ions along suitably constructed tubes. At the end of their journey these ions may be used to bombard materials.



Adapted from *Physical Review Illustration*

FIG. 192. A and B represent the D's or dees of a cyclotron. An ion originating at F spirals around and around until it emerges through a thin window W with very high speed.

(2) By the use of a *cyclotron*. Since this is a method which has been developed with great success and since its use has led to results of great importance in radiology, its basic principles will be described somewhat in detail.

Fundamentally, the method employed in the cyclotron consists in giving an ion at regular intervals a succession of low voltage pushes until it acquires the speed equivalent to a high voltage. The ion, after moving at a low speed through a half circle of small radius receives a push which sends it on at greater speed in a half circle of larger radius, at the end of the second half-circle, receiving another push it goes off moving still more quickly in a still greater half circle. The process continues, half circles being executed at greater and greater speeds and with greater and greater radii until after a few hundred or more revolutions, the ion is moving so quickly that its energy is the same as if it has fallen through a potential difference of a few million volts. In Fig. 192a, the curved dotted line represents a few turns of the spiral path of such an ion.

For the satisfactory operation of such a scheme, two things are necessary (1) The ions must be made to move in circular paths, and (2) the pushes must be properly timed. The first condition is easily realized by an application of the motor principle to which a somewhat general reference was made in

connection with the deflection, by a magnetic field, of cathode rays (sections 34 and 35), positive rays (section 43) and alpha particles (section 167). Let us examine this deflection a little more carefully.

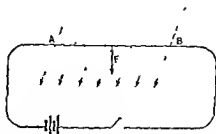


FIG 193 The wire  $AB$  when carrying a current and lying in a direction at right angles to a magnetic field is acted on by the force at right angles to the wire and to the field

According to the motor principle, when a wire such as  $AB$ , Fig 193, carries a current and lies in a direction at right angles to a magnetic field (represented by the lines with arrows) it is acted on by a mechanical force in a direction perpendicular to both the wire and the magnetic lines. In Fig 193, if the current, that is, the direction of positive flow, is from  $A$  to  $B$ , the force on the wire is in the direction represented by  $F$ .

Now a current is nothing but a flow of charges, hence a stream of any kind of electrified particles, whether cathode rays or positive ions, constitutes a current. If, as in Fig 194,  $CD$  represents the path of a stream of positive ions, there is a current in the direction  $CD$ . If, therefore, a magnetic field exists with lines running at right angles to the direction of motion of the ions a mechanical force must act on the ions. Since this force is always perpendicular to both the field and the current, it is not difficult to see that the ion path must be curved as in Fig 194. If the field is uniform and the speed of the ions constant, the curve is the arc of a circle.

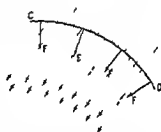


FIG 194 Particles carrying a positive charge when travelling in a direction  $CD$  at right angles to a magnetic field are subjected to forces  $F$  which make the particles move in the arc of a circle

Again, for ions moving at constant speed, the magnitude of the mechanical force is directly proportional to the strength of the magnetic field. It follows that the stronger the field, the more curved the path of the ion. On the other hand if the magnetic field is kept constant slowly moving ions are

deflected more readily than fast ones\* The curved paths of electrified particles are beautifully illustrated by cloud-track expansion chamber photographs Suppose that *HKLM* Fig 195*a* represents a cross section of a cloud-track chamber placed in the strong uniform magnetic field represented by the dotted lines If a photograph is taken when an ionizing particle is moving

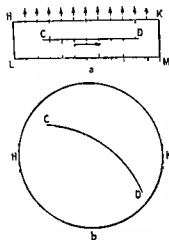


FIG 195 By using a cloud chamber the curved path of a charged particle in a magnetic field may be revealed

along *CD*, the trail of ions will be curved, somewhat as shown in the top view, Fig 195*b* Actual photographs showing this are reproduced in Fig 196 and Fig 197 In Fig 197 note (1) the closed circles which indicate the presence of very slowly moving particles, (2) the much less curved tracks, which indicate faster ions The two opposite curvatures of the trails of the faster ions provide evidence of both positive and negative particles (See section 199)

The circular trail in the lower half of Fig 196 shows clearly how, by the application of a suitable magnetic field, it is possible to make electrified particles move in circles To deflect particles of atomic size strong magnetic fields are necessary and the construction of a sufficiently powerful electromagnet for a good cyclotron is a big job in itself Here are a few details about

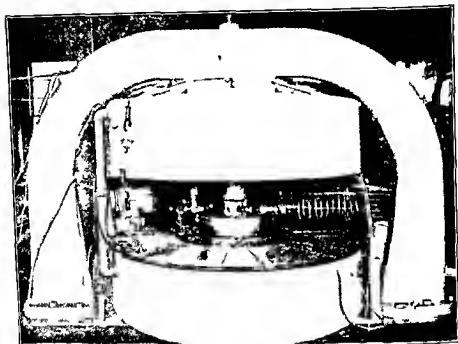
the magnet used in the cyclotron illustrated in Fig 198, one of the earlier instruments built under the direction of E O Lawrence of the University of California The pole faces are over two feet in diameter "The total weight of the magnetic circuit consisting of seven sections of cast steel is about 65 tons" The copper coils carrying the current which magnetizes the iron weigh about nine tons and are immersed in oil The large drum-like pieces shown in the photograph represent the outer casing surrounding these coils

To make sure that the ions whirl around after the manner depicted in Fig 192, the arrangement must be such that after the completion of each half-circle, an ion receives a push making it go a little faster in the next half-

\* A particle with charge  $e$  and velocity  $v$  is equivalent to a current  $ev$  Application of the motor principle shows that the mechanical force deflecting the particle is  $Hev$ , where  $H$  is the intensity of the magnetic field Since, when a particle of mass  $m$  moves with constant velocity  $v$  in a circle of radius  $r$ , the centripetal force is  $\frac{mv^2}{r}$ , we may

write  $\frac{mv^2}{r} = Hec$  or  $r = \frac{mv}{He}$ . Hence the smaller  $v$ , the smaller  $r$  or the more curved the path

marked *A* and *B* in Fig 192 a potential difference of several thousand volts which alternates from *A* positive and *B* negative to the reverse, a few million times a second. In the actual instrument *A* and *B* are hollow semicircular boxes frequently called *D*s or *dees* somewhat as shown in Fig 192*b*, which lie in the region between the pole pieces of the powerful magnet. In Fig 198, the position of the *dees* is clearly shown right at the center of the photograph.



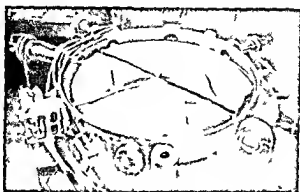
*Courtesy E. O. Lawrence*

FIG 198 A view of one of the cyclotrons constructed under the direction of E. O. Lawrence

Figures 199 and 200 reproduced through the kindness of W. J. Henderson are photographs of the *dees* used in a cyclotron constructed in the Physics Department of Purdue University.

When the machine is in use the air is exhausted from the boxes, a little gas such as hydrogen is allowed in at low pressure, and ions are created at the center by some such device as a heated filament. The value of the magnetic field and the frequency of the oscillating electric circuit are so chosen that during the time of a reversal of voltage between *A* and *B* the ion to be speeded up moves through exactly half a circle. Whenever therefore, an ion is pushed from *A* to *B* on the right side of the box in the next half cycle it will be pushed from *B* to *A* on the left and so continue on its circular motion in

paths which ever widen because of the increase in speed each half revolution. Just before the sides of the box are reached, the ions pass through a window into an observation chamber.



*Courtesy W. J. Henderson*

FIG. 199 The dees in the Purdue University cyclotron

Sometimes the ions emerge through a thin metal window into the surrounding air. When this is the case they strike the molecules of the air and cause them to emit light of a lavender color. The path of the ionic beam is then marked by a column of light extending for some distance from the window.



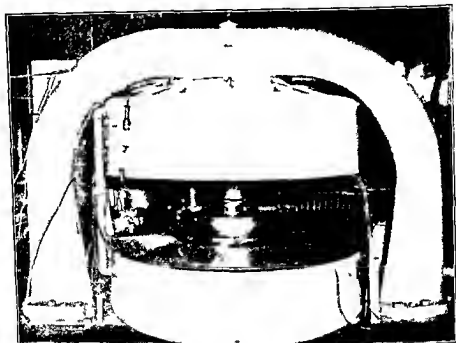
*Courtesy W. J. Henderson*

FIG. 200 Another view of the dees in the Purdue University cyclotron

This is beautifully shown in Fig. 201, a photograph taken by Professor Lawrence using deuterons (nuclei of heavy hydrogen) possessing some five or six million electron-volts of energy.

If a single push is given by a potential difference between the dees of 10,000 volts and an ion makes 200 revolutions, it has received 400 pushes or the equivalent of  $10,000 \times 400$  or 4,000,000 volts.

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*Courtesy E. O. Lawrence*

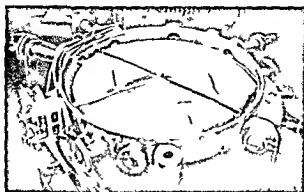
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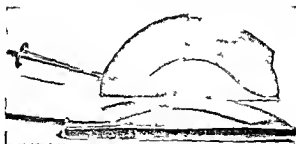
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*Courtesy W. J. Henderson*

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With the cyclotron described above, deuterons with 7 million electron-volts (7 mev) were developed. Following its construction cyclotrons were built at various centers, some of them developing deuterons possessing 20 mev of energy.

About 1940 a giant cyclotron, originally designed to develop particles possessing 100 mev, was under construction at the University of California. By way of contrast with Professor Lawrence's original machine, it is interesting to note that, in the giant instrument, 3700 tons of 2-inch steel plates



*Courtesy E. O. Lawrence*

1 to 201 A close up photograph showing the luminescence in air caused by a beam of high energy deuterons emerging from a cyclotron

were used to construct the magnet, whose pole pieces have a diameter exceeding 15 feet, with a gap between them of some 6 feet. The war interrupted the construction of this machine, but its magnet was put to use in the electromagnetic method of separating the uranium 235 isotope and so indirectly it played an important part in the harnessing of nuclear energy discussed in Chapter XVIII.

At the end of the war, work was resumed on the giant cyclotron. In mode of operation it differs somewhat from the original model and is more properly called a synchro-cyclotron. In the footnote on page 46, attention has been directed to the increase of mass of a cathode ray when its velocity is increased. Since this relativistic increase in mass, as it is called, applies to all high speed particles, it means that as the ions in a cyclotron are speeded up to high values their masses increase. Because of this change in mass it becomes more difficult to maintain resonating conditions. In the synchro-cyclotron this difficulty has been overcome by a method whose details need not be given in this book. It is sufficient to note that, as a pulse of ions originating at the ion source begins to spiral outwards, resonance can be

*maintained in spite of changing mass by slightly lowering (modulating) the frequency of the electrical oscillating circuit* In the giant cyclotron, which towards the end of 1946 was successfully operated, the pulse of ions makes some 10,000 revolutions, finally striking an internal target at a radius of some 80 inches, with about 200 mev of energy for singly charged particles like deuterons The time of flight from source to target is about 1000 micro-seconds When the machine is in operation a rapid succession of such pulses strikes the target

**189 The Betatron** — D W Kerst has developed a machine, called the *induction electron accelerator* or *betatron*, which is of great importance to the radiologist because by means of it electrons can be speeded up until they require 100 mev of energy, or even higher values These high speed electrons may be used for direct bombardment, or allowed to strike a target, thus creating x-rays of extremely short wave lengths

In common with the cyclotron, the electrons are constrained to move in circular paths because of a magnetic field By means of an injector, *J* in Fig 202, electrons from a hot filament are electromagnetically projected in a hollow evacuated box *B*, somewhat resembling a doughnut

in shape, which lies between the poles of a magnet Unlike the mode of acceleration in a cyclotron, the electrons are speeded up because of the induced electromotive force which results from a changing magnetic field To obtain a suitable changing field an alternating current is used in the electromagnet and the electrons are injected just after the current begins to rise at the beginning of a quarter cycle For the remainder of this quarter-cycle the current is growing and hence the strength of the magnetic field is increasing If, now, we think of an imaginary wire in the doughnut, represented by the dotted circle in the figure, the magnetic flux through it is increasing in this quarter-cycle, and hence there is an induced E M F in the wire whose magnitude is proportional to the rate at which the flux is increasing (Review section 2, Chapter I) Although there is no wire, an electron circulating in such

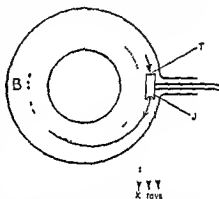
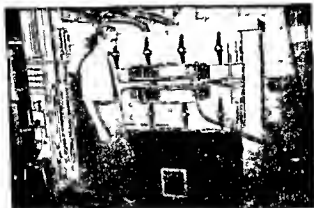


FIG 202 In the betatron electrons emerging from the injector *J* circulate in the doughnut-shaped vessel *B* (Adapted from diagram by Kerst)

an orbit experiences the same E M F and hence is accelerated. Since this acceleration occurs in each revolution which the electron makes, it will be seen that it can acquire an extremely high speed if it can make a sufficiently large number of revolutions. This is possible only if the electron can be kept in approximately the same orbit for many revolutions. In the betatron, electrons liberated at the injector after a few initial revolutions actually do settle down to rotation in an orbit whose radius remains constant\*. The



*Courtesy Dr. D. W. Kerst*

FIG. 203 A photograph of a 22 mev betatron at the University of Illinois.

photograph reproduced in Fig. 203 through the kindness of D. W. Kerst, will give the reader a general idea of the appearance of a 22 mev machine.

As long as the magnetic field is growing, there will be an induced E M F with resulting acceleration of electrons. In an actual machine, the acceleration of any particular group of electrons injected into the doughnut is continued for a time not exceeding one-quarter of a cycle of an alternating current whose frequency may range from 60 cycles per second to several hundred. A good idea of the times and distances involved in a 100,000,000

\* In the footnote at the bottom of page 266, it is shown that when a charged particle of mass  $m$  and velocity  $v$  rotates in a circular path in a magnetic field, the radius  $r$  of the orbit  $= \frac{mv}{He}$ . Since the product  $mv$  measures the momentum of a particle, it follows that the radius of the orbit will remain constant, even with changing mass and velocity, provided that the magnetic field increases in strength at the same rate as the momentum of the particle. Now the value of the momentum increases because of the force constantly acting on the electron, this force depends on the induced E M F and hence on the rate of change of magnetic flux within the orbit. It can be shown by using comparatively simple mathematics, that the radius remains constant if, at any instant, the magnetic flux within the orbit  $= 2\pi r^2 H$ . This condition is fulfilled in the betatron.

mev betatron may be had from the following figures given by Coolidge and Charlton. After rotating for  $1/240$  second, a pulse of electrons has made 250,000 revolutions, during each of which the average induced E M F was 400 volts, and has traveled a distance of some 800 miles.

But, it will be asked, what becomes of a pulse of electrons at the end of the quarter-cycle, or whatever shorter interval they are allowed to rotate? The answer is simple enough. The electrical arrangements are such that, at the end of the time interval, a condenser is made to discharge through what are called expanding coils, so placed that the condition for a fixed orbit is destroyed and the electrons spiral out of it until they hit a target, a piece of tungsten placed on the back of the injector. For the remainder of the whole cycle of alternating current, no electrons are in the doughnut, but at the beginning of the next another pulse is injected. Hence, an intermittent series of pulses strikes the target.

At the target, x-rays originate in the usual way. Strangely enough, the target does not become hot, because for some reason the efficiency of the process of converting the kinetic energy of these extremely high speed electrons is very high, according to Mayneord being 70 per cent for 20 mev betatrons. The output in roentgens is also high, Mayneord giving as approximate values, 100r per minute at 1 meter, for a 20 mev machine, and 1000r per minute for one developing 100 mev.

It will be seen then that the betatron provides the radiologist and others with a means of developing intense beams of x rays of very short wave lengths, and adds one more tool for experiments in radiation therapy. Moreover, it also opens up the possibility of using an electron beam itself in what we may call electron therapy, for in 1946 Kerst altered the controls in such a way as to bring the beam outside the instrument. Careful experiment alone will decide the value, if any, of electron therapy.

## CHAPTER XVI

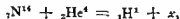
### TRANSMUTATION OF MATTER AND NEUTRONS

**190 Nuclear Bombardment** — The results obtained by bombarding substances with high speed particles have justified many times over the time and energy expended in the development of supervoltage machines. In this chapter reference is made to some of the important discoveries made in this way, with special emphasis on those relating to radiology. At the outset the student should become familiar with the following method of describing in symbols a nuclear interaction.

In section 36 it was pointed out that to describe an atom without ambiguity both its atomic weight and its atomic number must be given. Analysis by the mass spectrograph has shown in addition that on the atomic weight scale, masses of all atoms are given by numbers which depart from integers by very small amounts. With these facts in mind it is easy to see why an isotope of an element is frequently designated by the symbol  ${}_aX^b$ , where  $X$  is the customary chemical symbol,  $a$  is the atomic number, and  $b$  the mass number, that is, the integer which, with slight error, represents the atomic weight. Thus,  ${}_1H^1$  represents ordinary hydrogen,  ${}_1H$  or  ${}_1D^2$ , heavy hydrogen or deuterium,  ${}_2He^4$ , helium or an alpha particle, and  ${}_{80}Hg^{196}$ ,  ${}_{80}Hg^{198}$ ,  ${}_{80}Hg^{199}$ ,  ${}_{80}Hg^{201}$ ,  ${}_{80}Hg^{202}$ , and  ${}_{80}Hg^{204}$  various isotopes of mercury.

Whenever the nucleus of an atom moving at high speed strikes the nucleus of another atom and an interaction takes place, whatever the final products, the total nuclear charge and, at least to a first approximation,\* the total mass must remain constant. If, then, we write down an equation describing the nuclear reaction, the sum of the charges and of the masses on one side must equal the corresponding sums on the other side.

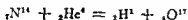
As an illustration, consider again the pioneer experiment of Rutherford when he obtained protons ( ${}_1H^1$ ) by bombarding nitrogen ( ${}_7N^{14}$ ) with alpha particles ( ${}_2He^4$ ). In symbols we can write



where  $x$  is a product which must have the mass number 17, since  $14 + 4 = 1 + 17$ , and the atomic number 8, since  $7 + 2 = 1 + 8$ . Since 8 is

\* This assumes the validity of the law of conservation of mass. Actually, in nuclear reactions, the total mass before may differ *very slightly* from the total mass after the reaction. This question is discussed and explained in section 203.

the atomic number or the distinguishing mark of oxygen,  $\tau$  must represent an isotope of this element of mass number 17, or we may now write



As we have already pointed out, long after Rutherford performed this experiment, analysis by the mass spectrograph showed that oxygen has an isotope of mass number 17.

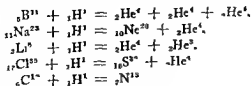
A still more abridged notation, making use of the symbol  $\alpha$  for alpha particle,  $p$  for proton, writes the above reaction  $\text{N}^{14} (\alpha, p) \text{O}^{17}$  which means that nitrogen of mass number 14 when bombarded with alpha particles, gives rise to an emission of protons and forms an oxygen isotope of mass 17. In nuclear reactions of this sort, it should be realized that the bombarding alpha particle actually penetrates the nucleus of the nitrogen atom, a temporary unstable compound being formed. This compound disintegrates into an oxygen atom and a proton. It should again be emphasized that out of millions of bombarding particles, only a few make collisions of such a kind that this temporary compound can be formed.

**191. Proton Bombardment** — Protons were the first artificially accelerated particles to be used in bringing about a nuclear transformation. In England, Cockcroft and Walton obtained alpha particles by bombarding a lithium target with protons, in accordance with the equation



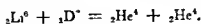
Although these experimenters used protons accelerated by some 150,000 volts and the transmutation can be brought about by less than 25,000 volts, the efficiency of such processes increases rapidly with the speed of the particles. For example, in one investigation it was shown that whereas for 250,000 volt protons there was one successful hit in  $10^9$  shots, for 500,000 volt protons, there were ten successful hits in the same number of shots. In many reactions it is desirable to have available particles speeded up by several million volts.

We conclude this section with a few other examples of proton bombardment which explain themselves



The last reaction is an example of *simple capture*

**192. Deuteron Bombardment** — High speed deuterons, that is, nuclei of the atoms of heavy hydrogen, have proved of the greatest importance in bringing about nuclear transformations. At this stage we give two examples. The first is described by the equation



Here, it will be noted, the lithium 6 isotope, on bombardment with deuterons, gives rise to alpha particles. This particular reaction is beautifully illustrated by Fig. 204, where *a* and *b* mark the paths of the two alpha particles ejected simultaneously in opposite directions.

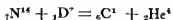


*Courtesy P. I. Dee, E. T. S. Walton and the Royal Society*

FIG. 204. *a* and *b* mark the paths of two alpha particles ejected simultaneously in opposite directions when a bombarding deuteron struck the nucleus of a lithium atom.

To make these long trails, the alpha particles initially must have had a great deal of kinetic energy. As this energy is a direct result of the nuclear process which takes place, it should be evident that the equation does not tell the whole story. For a complete discussion consideration must be given to the energy involved, a question considered in Chapter XVII.

A second example of deuteron bombardment which the student can interpret himself is given by the equation

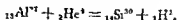


Other important examples will be given later.

**193 Artificial Alpha Particles** — By using helium in the dees of a cyclotron alpha particles with kinetic energy of the order of many million electron volts have been obtained. Since the energy of alpha particles from a radioactive product such as polonium is about 5 mev, we see what a powerful tool the cyclotron is. Moreover, not only can much faster artificial alpha particles be developed, but the intensities of the beams so obtained are the



equivalent of huge amounts of radioactive material. The following is an example of an alpha ray transformation



**194 Discovery of the Neutron** — The discovery of the *neutron*, a particle of mass number 1, but without any electrical charge was the result of certain experiments in which alpha particles from a radioactive source were the bombarding particles. In Germany, Becker and Bothe, when bombarding certain substances with alpha rays from polonium observed, particularly from the element beryllium, the emission of a radiation sufficiently penetrating to pass through tolerably thick sheets of metal. This radiation they considered to be similar in nature to gamma rays.

Following up this work, in France, Joliot and his wife, the daughter of Madame Curie of radium fame, were able with more intense sources of alpha rays, to show (1) that this radiation could penetrate an inch or more of lead, and (2) that, when it struck a substance like paraffin wax (which contains a large amount of hydrogen), protons were ejected with great energy. Note the two steps in producing the protons. Alpha rays strike beryllium, beryllium emits this penetrating radiation, supposedly of a gamma ray nature, the radiation strikes the paraffin wax, and protons are ejected.

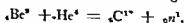
In England, at Cambridge, a particle without charge and with the mass of a proton had been sought for more than once. As far back as 1920 Rutherford had made reference to the possible existence of a neutron and about the same time Harkins at Chicago had pointed out that the problem of building heavy nuclei from light was much simplified if particles of this nature were available as building bricks. Now Chadwick working at Cambridge saw that it was highly probable that at least part of this penetrating radiation from beryllium consisted of neutrons and he set out to prove it.

It was clear that the radiation in question knocked protons out of paraffin wax, and it was a simple enough matter to measure the energy of the expelled protons, by examining how far they traveled. When this was done it was seen that it was extremely unlikely that they were knocked out of the wax by a gamma ray. For this to be possible the gamma ray photon would have had to possess some fifty million electron volts of energy, an amount far in excess of any probable value for such radiation. On the other hand, if the radiation consisted of high speed material particles, each with a mass approximately the same as that of a proton, the behavior of the emitted protons was exactly what was to be expected. The gamma ray hypothesis was something like assuming that a pellet of buckshot by striking a cannon ball could project

it forward, whereas the (neutron) particle hypothesis made only the reasonable assumption that it was a case of one cannon ball being struck forward by another

The ease with which the debatable radiation passed through thick layers of lead strongly suggested that the particles, if such they were, were uncharged. When a positively charged particle ploughs through matter there are strong forces of attraction between it and the negatively charged electrons in an atom near which or through which the particle is passing. In consequence, electrons are pulled out of many of the atoms in the path of the particle, the atoms are thereby ionized, and the moving charged particle is gradually slowed down as its energy is thus expended. With an *uncharged* particle, however, no such strong electrical forces exist and the slowing-down process is very much less rapid. Indeed, direct hits on the nuclei of the atoms are mainly responsible for the absorption of such a particle by the medium through which it passes. The slowing-down process of an uncharged particle, therefore, depends on two factors: (1) the degree of closeness, and (2) the masses of the nuclei. Actually the absorption is much greater in a light substance than in a heavy, because mass for mass, there are far more nuclei in the light than in the heavy substance. Moreover, the colliding particle, if of small mass, bounces off a very heavy nucleus with little loss of energy, whereas on collision with a light nucleus, such a particle transfers much of its energy to the struck particle. The fact, therefore, that lead is more transparent than light substances to the radiation in question is a strong argument in support of the hypothesis that this radiation from beryllium consists of a stream of neutrons, particles uncharged, whose masses are much less than those of the nuclei of lead atoms. If the mass of a neutron is of the same magnitude as a proton, the neutron in a head-on collision against a proton gives up all its energy to the proton, and the marked absorption of neutrons by substances containing hydrogen finds a ready explanation. (Later work, discussed in section 204, showed that the mass of a neutron is 1.0089 on the atomic weight scale. Compare this value with 1.00813, the mass of the hydrogen atom, and 1.00758, the mass of a proton.)

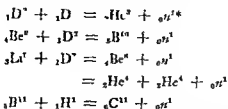
Chadwick, therefore, concluded that this extremely penetrating radiation consisted of a stream of neutrons generated according to the equation



where  $n^1$  is the symbol for a neutron

**195 Other Methods of Producing Neutrons** — A mixture of a radioactive source of alpha particles, such as radon (and its products) and

beryllium is a common source of neutrons. But neutrons are liberated in many reactions, a few of which are the following



In the  $\text{D} + \text{D}$  reaction, ice from heavy water can be the target for deuterons from a cyclotron. It is worth while noting that this same reaction has been used satisfactorily at the Mount Vernon Hospital, London, with an accelerating tube operated on 300,000 to 400,000 volts. Several years ago the statement was made that "this plant has so far given an output of neutrons equal to that produced by 30 curies of radon plus beryllium."

The exact amount of kinetic energy possessed by neutrons after a disintegration depends on the particular nuclei involved in the reaction. In the  $\text{Be}(\alpha, \text{n})$  reaction, groups of neutrons are liberated, some of them with energies exceeding 10 mev. In Chapter XVIII reference will be made to the atomic pile, from which a copious supply of slow moving neutrons can be obtained.

**196 Neutron Therapy** — We have described somewhat in detail the steps leading to the discovery of the neutron, as well as different methods of preparation, because there is ample evidence that biologically neutrons are of very great importance. Although, as we have seen, a neutron being uncharged does not ionize directly, indirectly it may cause intense ionization in a very short distance. For example, in passing through tissue with its high percentage of hydrogen, many neutrons are stopped (or slowed down) by direct hits (or less direct collisions) against protons. These protons then begin to move with the energy imparted to them by the neutrons, and being heavy charged particles cause intense ionization as they are slowed down. Since we have good reasons for believing that ionization is the primary cause of biological changes, it is only reasonable to expect strong biological reactions with neutron bombardment.

Direct evidence of this has been obtained in experiments which showed that neutrons were several times more effective in destroying malignant cells in

\*  ${}_1\text{D}^+ + {}_1\text{D}^+ = {}_2\text{He}^3 + {}_1\text{H}^1$  has also been observed

rats than x rays, and also in retarding the growth of wheat seedlings. In this connection we quote from an article by Gray, Reid and Mottram in *Nature* (Sept., 1939) "Neutron energy thus appears to be about ten times as efficient as gamma radiation energy in its lethal effect on bean roots."

In *Nature* (Jan., 1940) J. H. Lawrence writes "The intense beam of neutrons produced by the cyclotron has made it possible to investigate their biological effects on various objects such as bacteria, plants, *Drosophila* eggs, animal tumors and normal mammals. This new penetrating form of radiation has intense biological effects, even greater than x rays or gamma rays, on normal and tumor tissue, but when compared with x-rays, selectively affects some tissues more than others. Experiments on animals indicating that neutrons are more destructive to neoplastic tissue than to normal tissue suggested their trial in cancer therapy."

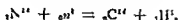
Both these quotations imply the use of some means of measuring effective amounts of neutron energy. Although a unit like the roentgen has not yet been standardized, much use has been made of the *n* unit, for fast neutrons. If the ionization chamber of a Victoreen condenser meter, shielded from gamma rays by lead, is placed in the path of a beam of neutrons and a dose of *a* roentgens is recorded, the customary procedure being followed, the neutron dose is said to be *a* of these *n* units. In other words, 1 *n* unit corresponds to 1 *r* unit as measured by this particular instrument. The ionization is due to the protons liberated when the bakelite walls of the chamber are struck by neutrons. This unit obviously does not fulfil all the conditions of a standard. A more exact one would make use of true energy absorption, and indeed, Pollard and Davidson, in their excellent book on *Applied Nuclear Physics*, have suggested that 1 *n* might be defined as that quantity which produces 165.4 ergs per cc. of tissue. This particular number is chosen because it is twice the energy absorbed per roentgen per cc. of tissue. No such unit, however, has been adopted and current practice is to use the *n* unit as defined above.

Many investigations have been and are being made concerning possible specific biological action of neutrons, as well as concerning the relative effectiveness of x-rays with dose measured in roentgens and of neutrons with dose in *n* units. These investigations emphasize that "some tissues are affected more than others by neutron rays" (Lawrence) and that "further investigation is most certainly warranted to establish more definitely the degree of superiority, if any, of neutron therapy over the more conventional procedures which employ x-rays" (Stone and Hamilton). Regarding neutrons of high energy, Mayneord states that "the only hope for this type of therapy lies in a selective tumor effect and as yet (1946) such has not been observed." Con-

cerning slow neutrons Mayneord sees possibilities arising from the reaction



because gamma rays are emitted, and also in the reaction



(See Chapter XVII)

**197. Protection against Neutrons** — From what has been stated in the previous section, it will be evident that it is highly necessary to provide adequate protection against possible neutron bombardment. It should be equally clear that a substance like lead is practically useless as an absorbing material. Neutrons will pass through several feet of lead. In actual practice, protection is provided by surrounding a neutron source with tanks of water, use being made of the slowing down of the neutrons by impacts against protons. After some twenty collisions, a five million electron volt neutron is slowed down to such an extent that its energy is only about one tenth of an electron volt. Certain nuclei strongly absorb slow neutrons. If boron, for example, is added to the water in the tank, it becomes a still better absorbing layer.

**198. Neutron Bombardment and Detection** — Because of the ease with which uncharged neutrons can enter the nuclei of atoms, this particle has proved particularly valuable in bringing about nuclear reactions. An excellent illustration of this is found in the fact that whereas with the fastest alpha particles available, no disintegrations had been obtained with elements of atomic number greater than 19 before the discovery of neutrons, after the discovery it was soon shown that elements of high atomic weight such as gold were readily disintegrated. In this work the name of the Italian physicist Fermi, now in the United States, is outstanding.

Nuclear reactions can be brought about by both slow and fast neutrons, but the probability of a particular reaction taking place is largely a matter of experiment. Two examples of nuclear changes brought about by slow neutrons have been given at the end of section 196. Another example, in which an alpha particle is one of the final products, is the following



This is an especially interesting reaction, because Paneth and co-workers not only identified spectroscopically the small amount of helium manufactured but also measured the volume liberated when the source of neutrons acted for a measured time. Some idea of the delicacy of Paneth's measurements

is obtained from the fact that he was dealing with volumes of the order of one ten-millionth of a cubic centimeter

This reaction is important for another reason, because it is the basis of a method of detecting and counting slow neutrons with an ionization chamber and counter (See section 171) As already emphasized, neutrons do not themselves ionize Suppose, however, that a beam of slow neutrons enters the ionization chamber of a counter designed for alpha rays which is filled with the gas  $\text{BF}_3$ , boron trifluoride The  $\text{B}^{10}(n, \alpha)\text{Li}^7$  reaction takes place and the emitted alpha rays can be counted in the usual way. Alternately, the chamber can be filled with an ordinary gas and lined with a thin layer



*Courtesy Professor Pierre Demers*

FIG. 205 Enlargement showing the tracks in a photographic emulsion of an alpha particle (on the left) and a triton (on the right) which resulted from a neutron coalescing with a  $\text{Li}^7$  nucleus

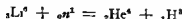
of boron In either case the number of counts is proportional to the number of alpha particles and hence to the number of neutrons giving rise to them

Fast neutrons could be detected with the same arrangement by placing in the path of the neutron beam a thick block of paraffin to slow them down Fast neutrons can also be detected and counted if recoil protons are generated in the gas of the chamber Recoil protons arising from collisions in which fast neutrons give up most of their energy to protons which they hit must not be confused with protons arising from nuclear disintegrations, such as the following



This is an important reaction for another reason which will appear in Chapter XVII

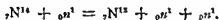
Figure 205, a photograph reproduced through the kindness of Professor Pierre Demers, of the University of Montreal, is a good example of the photographic method of revealing tracks of particles, and also a striking visualization of the nuclear reaction



Professor Demers reports that a slow neutron emerging from the atomic pile at Chalk River, Ontario, struck a nucleus of a  $\text{Li}^7$  atom embedded in a

photographic emulsion. The middle arrow in the photograph marks the spot where the alpha particle and the triton, as the nucleus of the isotope  $H^3$  is sometimes called, originated. The alpha ray track is the denser one on the left, the triton on the right. The equivalent range in air of the alpha particle, as determined from its path length in the emulsion, is 1.07 cm, which means that its initial kinetic energy was of the order of 2 mev. The actual length of the path in the emulsion is a small fraction of a millimeter.

Certain nuclear reactions initiated by neutron bombardment liberate neutrons, as, for example,



In this particular type, as will be seen in Chapter XVII, no energy is released. Of far greater importance is the phenomenon of fission, in which the nuclei of certain heavy atoms are split by colliding neutrons with liberation of neutrons and also with a large amount (about 200 mev) of energy per fission. This question is discussed in detail in the next chapter.

**199 The Positron, the Mesotron, and Cosmic Rays** — In section 41 it was stated that at all times there are a few stray ions present in air. The study of the cause of the feeble conductivity arising from these ions led to the conclusion that the earth's atmosphere is traversed by a radiation of as yet unknown origin, coming in "from out of the everywhere into here." This radiation is now called cosmic rays. Hundreds of investigations have been made and hundreds are in progress, concerning the nature of these rays. Although much information has been found, the question of cosmic rays presents many problems still unsolved and in this text details would be out of place. As a result of these researches, two new particles have been discovered, the positron and the meson or mesotron. In the discovery of these particles cloud track photographs played an important part.

Figure 197 reveals a phenomenon which frequently occurs when a cosmic ray strikes a substance like the metal plate. As is seen in this photograph a shower of electrified particles, originating as a result of the impact of a cosmic ray, has emerged from a center marked G, in the material surrounding the cloud-track chamber. When this photograph was taken, the particles had to traverse a magnetic field, and hence the curvature in opposite directions strongly suggests that there are two kinds, one with a positive charge, the other with a negative. The only known negatively charged particle is an electron, but we have become familiar with two positive particles, alpha rays and protons. The assumption that the path curved in one direction is caused by an electron is greatly strengthened by the appearance of the trail, because the little

dots representing ions look exactly the same as those obtained with beta rays and fast electrons. Moreover, estimates of the energy of such particles, based on the measured curvature of their tracks (and the assumption that they are electrons), lead to values in agreement with observations of their ionization and their penetrating powers. We get into difficulties, however, when we try to ascribe the trail of opposite curvature to either an alpha particle or a proton. This trail also looks exactly like that of an electron, and not at all like the heavy continuous line representing the trail of an alpha particle or of a proton. If, disregarding this similarity to the path of an electron, the particle is assumed to be either an alpha ray or a proton and its energy is calculated making use of the amount of curvature, values are obtained far too small to account for the observed penetrating power. All the evidence, therefore, indicates that the trail is caused by a positively charged particle of mass comparable with that of an electron. When cosmic ray cloud-track photographs were first taken, no such particle was known to exist, but this was the conclusion to which Anderson in the United States, in 1932, and not long afterwards Blackett in England were driven. This new particle was given the name *positron*.

Another good example of the trick of a positron is shown in Fig. 196.

Although the positron is, in many ways, the counterpart of the electron, it differs from it in one important respect, because unlike the ubiquitous stable electron, the positron is an extremely short-lived unstable particle. If electrons are about, and they are ubiquitous, a positron and an electron will embrace giving rise to gamma radiation, again a matter more fully explained in the next chapter.

The *mesotron* revealed its existence in expansion chambers as a track, heavier than that of an electron or a positron, but less heavy than that of a proton. It has now been definitely established that it is an unstable, short-lived particle, which may be either positive or negative, having a mass of the order of 200 times that of an electron. Mesotrons have not yet been created or released by artificial means. There is evidence, however, that by suitable nuclear bombardment with particles possessing a few hundred million electron volts, this may be possible. This is one reason machines are being developed for producing particles with such large amounts of energy.

In concluding this brief reference to cosmic rays, it is interesting to note that there is evidence that the rays come in from outer space with energies exceeding a thousand million electron-volts.

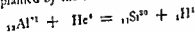


## CHAPTER XVII

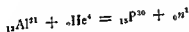
### ARTIFICIAL RADIOACTIVITY, MASS AND ENERGY

**200 Artificial or Induced Radioactivity** — In 1934 Mme and M Jolot, working in France, found that aluminum foil, which had been bombarded with alpha rays for a few minutes, emitted positrons *after the bombardment had ceased*. The foil could be removed from the source of alpha rays — taken into another room altogether — and when brought near a charged electroscope, caused it to lose its charge just like a natural radioactive body. The aluminum soon lost its acquired radioactivity, decreasing to half strength in about three minutes, but the effect was unmistakable. Aluminum can be made temporarily radioactive by bombardment with alpha rays. What exactly happens?

An examination of the transmutation products resulting from the bombardment of aluminum with alpha rays, shows that *during the bombardment* sometimes protons are emitted, sometimes neutrons and positrons. The proton emission is readily explained by the transformation



To account for a neutron emission, the following transmutation must take place

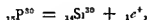


In this case, the products of the transformation are a neutron and an element which must be phosphorus, because its atomic number is 15. Phosphorus is a well-known element with a stable isotope of mass number 31, but it has no known stable isotope with mass number 30. Mme and M Jolot, therefore concluded that this isotope of phosphorus is unstable or radioactive, emitting positrons when it "explodes". What happens then is this. The original bombardment of the aluminum manufactures a certain amount of  ${}_{15}\text{P}^{30}$ . On ceasing fire with the alpha rays, the foil is removed and embedded in it are these new unstable or radioactive atoms. When they explode, they shoot off positrons.

Since a positron has an almost negligible mass and one unit positive charge, the nucleus left behind after the explosion has practically the same mass as be

fore, but an atomic number one less. In the case of  $_{15}\text{P}^{30}$  the nucleus left, therefore, must have an atomic number of 14, hence it must be silicon

We may write

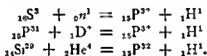


where  $_1e^+$  is the symbol used for a positron

The half-period of  $\text{P}^{30}$  is a little less than three minutes

To distinguish an unstable, radioactive isotope of an element from a stable one, particularly when the element occurs in nature only in its stable form, the prefix *radio* may conveniently be used. Since, however, the same element may have more than one radioactive isotope, the mass number should also be specified. The element phosphorus, for example, has a radioactive isotope of mass number 32, as well as of 30

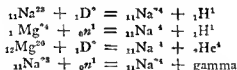
Radiophosphorus<sup>32</sup>, or  $_{15}\text{P}^{32}$ , is of much greater importance to the radiologist than  $_{15}\text{P}^{30}$  because its half-period of 14.3 days is so much longer. The following equations describe three of the several ways in which it can be prepared



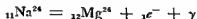
When  $_{15}\text{P}^{32}$  disintegrates, beta rays are emitted, hence  $_{16}\text{S}^{32}$  must be the final stable product, in accordance with the relation



A second interesting example of a radioelement is  $_{11}\text{Na}^{24}$  which may be manufactured by methods such as the following



When radiosodium<sup>24</sup> disintegrates, with a half period of 14.8 hours,  $_{12}\text{Mg}^{24}$  is the stable product and beta and gamma rays are liberated. In symbols we write



Radiosodium<sup>24</sup> may readily be made in quantities which are the equivalent of thousands of dollars worth of radium

In passing it is interesting to note that sodium has in all the following five isotopes four of them radioactive with half periods given in brackets.  $\text{Na}^{21}$  (23 sec),  $\text{Na}^{22}$  (3.0 years),  $\text{Na}^{23}$  (stable),  $\text{Na}^{24}$  (14.8 hours), and

$\text{Na}^{23}$  (62 sec). There is nothing particularly unique about this, for it applies to many other elements. We list the isotopes of carbon because, like sodium and the elements listed in Table XXXV, it is of importance in biological problems. Carbon has in all three radioactive and two stable isotopes  $\text{C}^{10}$  (8.8 sec),  $\text{C}^{11}$  (20.5 min),  $\text{C}^{12}$  (stable, 98.9 per cent),  $\text{C}^{13}$  (stable, 1.1 per cent),  $\text{C}^{14}$  (1000 years).

In Table XXXV, the numbers in brackets after beta particles give maximum values of their energies. The same applies to the energy possessed by the photons of gamma radiation (see section 202).

TABLE XXXV

Radioelement	Radiation and Energy	Half period
$\text{H}^3$	beta <sup>-</sup> (0.015 mev)	31 years
$\text{C}^{11}$	beta <sup>+</sup> (0.95)	20.5 mins
$\text{C}^{14}$	beta <sup>-</sup> (0.145)	1000 years (?)
$\text{N}^{13}$	beta <sup>+</sup> (0.92, 1.20), $\gamma$ (0.28)	9.9 min
$\text{Na}^{22}$	beta <sup>+</sup> (0.58)	3 years
$\text{Na}^{24}$	beta <sup>-</sup> (1.4), $\gamma$ (1.38, 1.73)	14.8 hrs
$\text{P}^{32}$	beta <sup>-</sup> (1.69)	14.3 days
$\text{S}^{34}$	beta <sup>-</sup> (0.17)	87.1 days
$\text{K}^{41}$	beta <sup>-</sup> (3.5)	12.4 hrs
$\text{Ca}^{45}$	beta <sup>-</sup> (0.2), $\gamma$ (0.7)	180 days
$\text{Fe}^{59}$	beta <sup>-</sup> (0.26, 0.46), $\gamma$ (1.10, 1.30)	47 days
$\text{Co}^{60}$	beta <sup>-</sup> (0.31), $\gamma$ (1.10, 1.30)	5.3 years
$\text{Si}^{31}$	beta <sup>-</sup> (1.32)	55 days
$\text{I}^{131}$	beta <sup>-</sup> (0.03, 0.69), $\gamma$ (0.367, 0.080)	8 days

**201. Biological Uses of Radioelements**—Broadly speaking, the biological and medical uses of radioelements may be divided into two main classes (a) as tracers or indicators or spy atoms, and (b) as therapeutic agents. The use of radioactive materials as indicators depends on two facts. (1) The ionization method of detecting and measuring small quantities of a radioactive substance is so sensitive that it is possible to measure quantities millions of times less than the smallest amount detectable even by the spectroscope. Hevesy and Paneth, who were pioneers in the use of radioactive elements as indicators, state that whereas "spectroscopy can often not only detect, but even measure, much smaller amounts, down perhaps to  $10^{-9}$  or  $10^{-10}$  gm. only the methods of radioactivity are able exactly to determine quantities of matter of the order of, say,  $10^{-17}$  gm." (2) Stable isotopes and unstable or radioactive isotopes of the same element have identical chemical properties and, therefore, cannot be separated by chemical means.

Now long before the discovery of artificial radioelements it was realized, notably by Hevesy and Paneth, that if a small amount of a radioactive isotope was mixed with a large amount of a stable isotope of the same element, the activity of the radioactive portion would reveal the presence of the whole quantity. Bismuth and radium E, for example, are isotopes with the same atomic number 83, and if these substances are mixed, it is impossible to separate them by chemical means. But, wherever the mixture is, its presence can be detected by the signals which the unstable atoms of radium E send out in the form of ionizing beta radiations. Moreover, because of the extreme sensitivity of the ionization test, only a very small amount of the radioactive tracer or indicator is needed. This particular example has been given, because bismuth is used in the treatment of syphilis, and by the addition of radium E, it was possible to investigate "the rate at which different bismuth compounds are resorbed after injection" (Hevesy and Paneth).

The discovery of the comparative ease with which it is possible to manufacture radioactive isotopes of elements present in plants and animals has naturally led to their use in biological and physiological investigations.  $P^{32}$ , for example, because of its fairly long half-period and its importance in body metabolism has been used in the study of many problems. A small amount of the radioactive element, mixed with sodium phosphate, for example, is introduced into the body by the mouth and the subsequent behavior of the phosphorus traced by the use of a sensitive detector of ionization, such as a Geiger-Mueller counter. It is not the object of this book to go into details concerning results of such investigations, but it is interesting to note that it has been shown that the role of phosphorus in bones, for example, is a dynamic process, that is, atoms of this element are constantly being replaced by the arrival of fresh atoms.

The same methods applied to plants have shown that in the leaves of maize and sunflowers, phosphorus atoms wander about, the same atom moving from one leaf to another in the course of a few days.

A different method of detection of the tracer  $P^{32}$  atoms is nicely illustrated by Fig. 206, a photograph originally taken by Dr. Perry Stout and reproduced through the courtesy of *Radiology* and Dr. J. M. Cork, the author of an article in that journal. The photograph shows the concentration of phosphorus in the stems of the leaf of a tomato plant. In this case the plant is grown in a solution containing a small amount of  $P^{32}$ . Subsequently a leaf was placed in contact with the emulsion of a photographic film which was affected by the beta rays from the radioactive phosphorus.

Although the half period of  $Na^{24}$  is much shorter than that of  $P^{32}$ , it also has proved useful as an indicator. Common salt, to which a little  $Na^{24}$  has

been added, can be detected in a hand ten minutes after it has been swallowed, and when a solution of common salt is injected intravenously in one hand, twenty seconds later sodium appears in the other.

A good example of the use of  $\text{Na}^{24}$  is given by a somewhat extensive investigation by Smith and Quimby. In this work normal saline was injected intravenously into some 200 patients with peripheral vascular disease, and "the circulation of the blood was traced by following (with a Geiger-Mueller counter) the sodium it carried."

As another illustration of the use of a radioelement as a tracer, we quote from an article by Dr. J. L. Lawrence, on the use of radioiron in investigations by Whipple and associates, and Auston and Greenberg: "When radioactive ferrous salts were given orally to normal and anemic animals and the animals were sacrificed at various periods thereafter, the uptake of the tagged iron, as determined by Geiger counter measurements, was from 4.1 to 12.7 per cent in the anemic animals and 0.08 to 0.24 per cent in the normal controls. These studies indicate that the uptake of the radioiron is determined by the need of the body for iron."

According to Evans one of the experts in the field of radioactive tracers, in some branches of such work, only a single spy or tracer atom is needed for each ten billion to a million billion normal atoms.

The fact that certain elements or compounds appear in excess in local regions suggests the therapeutic use of radioelements for diseased areas. For example, iodine concentrates in the thyroid gland, a fact amply verified by the use of  $\text{I}^{131}$  as a tracer element. It follows that, in diseased conditions, if iodine containing the radioactive variety is administered to a patient, the radiation from the  $\text{I}^{131}$  might have beneficial effects. There is evidence



*Courtesy Radiology and Dr. J. M. Cork*

FIG. 206 Auto-radograph showing the distribution of radiophosphorus in the leaf of the tomato plant. (Original by Dr. Perry Stout.)

that this is true in the treatment of hyperthyroidism, but this whole field is so new that much careful experimenting is necessary before final conclusions can be reached

The possible use of radioelements as therapeutic agents is indicated by the results of another investigation, by Evans and Qumby, dealing with a comparison of the effects on white mice of whole body roentgen radiation and of radioactive sodium. They report that "it has been found that 10 microcuries of radioactive sodium per gram of body weight injected subcutaneously in the normal mouse are equivalent in effect to 100 roentgens of heavily filtered 200 Kv roentgen rays"

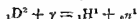
More striking is the statement by Rhoads and Solomon that "radioactive phosphorus is probably the best therapeutic agent available at the present time (1946) for polycythemia vera"

These few examples should give the reader a general idea of a whole field of activity, in which, although many investigations have already been carried out, especially with phosphorus and iodine, the future has amazing possibilities. One of the most important results of the recent developments in nuclear energy discussed in Chapter XVIII is the ease with which large quantities of radioactive isotopes may be manufactured. Many, but not all, of these are listed in Table XXXV, and it will be seen that emitters of both beta and gamma rays are available. In this table, as previously indicated, energy values have been given. The significance of this will be understood better after a study of the work in the next few sections.

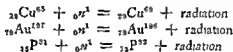
**202 Gamma Ray Bombardment** — In sections 123, 130, 132, and 135 reference was made to the view that radiation must be thought of as existing in energy units called quanta. It will be recalled that for radiation of wave length  $\lambda$ , a quantum has the value  $\frac{h \times c}{\lambda}$  where  $h$  is Planck's universal constant of magnitude  $6.56 \times 10^{-27}$  erg  $\times$  sec, and  $c$  represents the velocity  $3 \times 10^{10}$  cm per second with which all electromagnetic waves travel. It was pointed out also that sometimes it is necessary to think of radiant energy traveling through space as photons, each photon having a quantum of energy. Using this point of view, for example, we saw in section 132 that it was easy to explain the production of recoil electrons when x-rays are scattered. In section 135 it was also shown that, if we express in electron-volts the energy of a photon of radiation of wave length  $\lambda$  angstroms, we obtain the result

$$\text{Energy of photon} = \frac{1.23 \times 10^4}{\lambda(\text{angstroms})} \text{ electron volts}$$

For a gamma ray of wave length 0.0056 angstrom, one of the shortest emitted by radium C, this gives the value  $2.2 \times 10^6$  e.v., that is, over two million electron-volts. If, now, we keep in mind that photons may have energy values as large as this, it should not be surprising to learn that nuclei of some atoms can be disintegrated by gamma ray bombardment. We note two examples. (1) Using gamma rays from thorium C'', of magnitude 2.62 million e.v., Chadwick and Goldhaber disintegrated deuterons into protons and neutrons, in accordance with the equation



It follows that, if a proton picks up a neutron to form a deuteron, the converse reaction should take place and energy be released as radiation. This, indeed, is not uncommon when a neutron is captured. A few examples are



In passing, it may be noted that this process is a common way of making radioactive isotopes, since many of the products, like  $\text{Cu}^{60}$ ,  $\text{Au}^{198}$  and  $\text{P}^{32}$  are unstable.

(2) Our second example of photodisintegration is the following



To bring about the disintegration of  $\text{Be}^9$ , the photons must have energy exceeding 1.4 mev. Energies far in excess of this amount are necessary to disintegrate the great majority of stable isotopes, and as yet disintegrations by gamma ray bombardment are not numerous. However, with betatrons and other instruments developing x-rays by the stoppage of electrons possessing 200 mev or more, the future should reveal many more photodisintegrations.

Mayneord points out the possibility of biological effects resulting from the photodisintegration of elements in tissue, such as C, O and N. If 20 mev are available, carbon, for example, can be disintegrated in accordance with



${}_6\text{C}^{11}$  being radioactive, biological effects are to be expected.

It should be noted that the probability of reactions of this kind taking place is not high, photons with 20 mev being more likely to give up energy to recoil electrons or for the formation of pairs. (See section 206.)

**203. Mass and Energy** — The work on disintegration and transmutation has shown that the nuclei of atoms must be complex in structure. In pres-

ent day physics one of the important problems is the elucidation of this structure. It is not our purpose to go into details about the information which so far has been obtained, but there is one question relating to nuclear structure and nuclear transformations which is so fundamental that some explanation of it must be given. This has to do with the equivalence of mass and energy.

In section 190 it was pointed out that, in equations dealing with nuclear reactions, the sum of the mass numbers on each side of the equation must be the same. *Thus, however, is true only to a first approximation.* If use is made of the accurate values of atomic weights found by the mass spectrograph, a few of which are listed in Table V, section 48, a very slight discrepancy between the sums is found. As an example consider again the reaction



If we set down in a kind of balance sheet, the accurate mass values, we see at once that the sum on the right side of the equation is distinctly less than the sum

BEFORE		AFTER	
Mass of $\text{Li}^7$	7.01818	Mass of $\text{He}^4$	4.00386
Mass of $\text{H}^1$	1.00813	Mass of $\text{He}^4$	4.00386
Sum	<u>8.02631</u>	Sum	<u>8.00772</u>

on the left. The discrepancy is not great, being only 0.0186, but it is far too large to be described to experimental error. In the transaction, apparently mass has been lost. What has become of it?

The answer to a question of this kind had already been given by Einstein, who showed that *every form of energy has an equivalent mass*. It is a wrong, although a very common, idea, to consider mass and matter synonymous. It is perfectly correct to state that inert matter has mass, but the converse is not necessarily true, because all mass is not associated with matter. Energy, too, has mass. A photon, for example, has mass, and the mass of a proton is greater when it is moving than when it is at rest by the mass equivalent of its kinetic energy.

In symbols, Einstein's law is written

$$E = mc^2 \quad \text{or} \quad m = \frac{E}{c^2}$$

where  $E$  represents the amount of energy,  $c$  is the velocity of light, and  $m$  the equivalent mass. Let us put the matter in numbers.

The mass of a hydrogen atom  $= 1.66 \times 10^{-24}$  gm, and  $c = 3 \times 10^{10}$  cm per sec. If, therefore, it was possible to annihilate a hydrogen atom, although inert matter would disappear, the mass would now be associated with an



amount of energy given by

$$E = 1.66 \times 10^{-24} \times 9 \times 10^{20} \text{ ergs}$$

If this energy is expressed as  $V$  electron volts, then we write (see section 35)

$$\frac{V}{300} \times 4.8 \times 10^{-10} = 1.66 \times 10^{-24} \times 9 \times 10^{20},$$

from which

$$V = 933 \text{ mev}$$

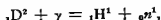
Thus, we may state that the disappearance of about 1 unit of matter on the atomic weight scale should release about 933 mev, hence the disappearance of 0.001 of a unit releases about 0.933 mev. Approximately we may use 1 mev as the equivalent of 0.0011 of an atomic weight unit.

On this view, then, *conservation of mass holds only if we include the mass equivalent of any energies involved in a transaction.* The truth of this was proved by direct experiment for the reaction  ${}_3\text{Li}^7 + {}_1\text{H}^1 = {}_2\text{He}^4 + {}_2\text{He}^4$ . In one experiment it was shown that when the bombarding proton had 300,000 e.v. of kinetic energy each of the emitted alpha particles is ejected with 8.7 mev of kinetic energy. When these energy values are taken into consideration and Einstein's law is applied, there is agreement to a high order of accuracy between the total mass on one side of the equation and the total on the other. Our balance sheet now is written \*

BEFORE		
Mass of lithium <sup>7</sup> atom	.	= 7.01818
Mass of bombarding hydrogen <sup>1</sup> atom		= 1.00813
Mass equivalent of 300,000 e.v.	$= \frac{300,000}{933,000,000}$	= 0.00032
Total		<u>8.02663</u>
AFTER		
Mass of 2 helium atoms = $2 \times 4.00386$		= 8.00772
Mass equivalent of 8,700,000 e.v.	$= \frac{8,700,000}{933,000,000}$	= 0.00933
Mass equivalent of 8,700,000 e.v.		= 0.00933
Total		<u>8.02638</u>

\* The objection may be made to the numbers given in the balance sheet that the mass of the *nucleus* should be used, not that of an *atom*. This is perfectly true, but no error is introduced into the calculations because the atomic mass is substituted for the nuclear mass on each side of the equation. Putting it in another way we have added to the nuclear masses on each side the masses of four extranuclear electrons.

**204 Mass of the Neutron** — By applying the law of conservation of energy (or of mass) in its exact form to the nuclear reaction



it is easy to evaluate the mass of a neutron (See again section 202) On the left hand side of this equation, the mass is 2 01472, for  $\text{D}^2$ , plus 2 62/933, or 0 00281, the mass equivalent of 2 62 mev, making a total of 2 01753 On the right hand side, we must record 1 00813 for  $\text{H}^1$ , plus  $x$ , the mass number of the neutron, plus the mass equivalent of the energy of motion of the disintegrated particles Now, by measuring the amount of ionization produced by a proton, Chadwick and Goldhaber showed that the energy of motion of both the proton and the neutron in this reaction was about 0 5 mev Since this amount has a mass equivalent of 0 00053 unit, the total to be recorded on the right side of the equation is

$$1\ 00813 + 0\ 0053 + x, \text{ or } 1\ 00866 + x$$

Hence,

$$2\ 01753 = 1\ 00866 + x,$$

or  $x = 1\ 0089$ , to 5 significant figures

**205 Emission of Gamma Rays in Nuclear Reactions** — In the proton lithium reaction the form of the energy released was kinetic, but this is not the only kind which may appear Sometimes radiant energy is released when a nuclear reaction takes place For example, when protons bombard boron<sup>11</sup>, gamma rays are emitted as a result of the transmutation



Since the mass of  $\text{B}^{11} = 11\ 0128$

and the mass of  $\text{H}^1 = 1\ 0081$

or the total  $= 12\ 0209$

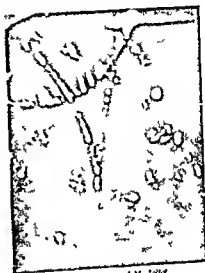
and since the mass of  $\text{C}^1 = 12\ 004$ ,

we see that the lost mass, or more accurately, the loss of mass associated with matter  $= 0\ 017$  unit Hence, energy is released to the extent of  $17 \times 0\ 93$  or about 16 mev Experimentally, when this reaction takes place an emission of gamma rays is observed, with energy reaching a maximum value of 16 6 mev From observation and measurement of the energy of gamma rays emitted in such a reaction, valuable information is obtained about the various states or conditions in which the nucleus of a stable atom may exist

This emission of gamma rays must not be confused with the gamma radi-

tion from a radioelement. In that case, an unstable nucleus is formed as a result of the nuclear reaction. When subsequently, such a nucleus explodes because of its instability, gamma rays are sometimes emitted.

**206 Pair Production** — We have seen in section 202 that the photon of a gamma ray may bring about the disintegration of a stable nucleus. In this case, the photon disappears, its energy being absorbed by the disintegrating nucleus. Earlier in this book, emphasis was laid on the fact that, in the photoelectric effect, a photon completely disappears, its energy being used to eject the photoelectron. A third way in which a photon may completely disappear provides a striking example of mass associated with energy appearing as equivalent mass associated with material particles. In what is known as *pair production*, a photon, when in a region close to the nucleus of an atom, disappears, giving rise to the birth of an electron and a positron. The phenomenon is beautifully shown in Fig. 207.



Courtesy of J. R. and M. J. J. J.

**FIG 207** An electron pair. The two tracks curved in opposite directions and emerging from the same point are the paths of a positron and an electron created by the disappearance of a gamma ray.

For pair production to take place, the photon must possess sufficient energy and it must be in the field of the nucleus of an atom, the heavier the better. It is easy to estimate the necessary amount of energy, since it is well known that the rest or slow-speed mass of an electron (and a positron) is 0.00055 unit on the atomic weight scale. Since this is the mass equivalent of  $0.00055 \times 933$  or about 0.51 mev of energy, at least  $2 \times 0.51$  or 1.02 mev is necessary to give birth to an electron pair. To produce a pair giving rise to tracks like that shown in Fig. 207, the original photon must have had energy considerably in excess of 1.02 mev, the excess over this amount going into the kinetic energy of the particles.

When photons of sufficiently high energy are used, pair production is of importance if tissue is irradiated. In section 133, it was pointed out that, as we use higher and higher potential differences to generate x-rays, absorption due to recoil electrons becomes of greater importance than that due to the

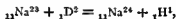
photoelectric effect From 200 kilovolts up, recoil electrons predominate. If the radiation consists of photons with energy around 50 mev, pair production is the most important factor causing absorption.

As might be expected, the converse to pair production can take place and has been observed experimentally When a positron and an electron come together, they disappear giving birth to energy in a process which can legitimately be called annihilation of matter. Obviously the union produces 1.02 mev of energy in the form of gamma radiation.

### PROBLEMS AND QUESTIONS

1 Enumerate three ways of obtaining voltages of the order of 50,000, and one way of obtaining, 1,000,000 volts

2 With reference to the equation



explain (i) what experimental fact this tells you, (ii) the meaning of the subscript and superscript numbers, (iii) why  ${}_{11}\text{Na}^{24}$  is called radiosodium

3 What is the difference between stable and unstable isotopes? Give one example of each class

4 Write down the transformation equation when radiosodium is formed by the bombardment of magnesium (atomic weight = 24, atomic number = 12) by neutrons

5 (a) When sulphur (atomic weight 32, atomic number 16) is bombarded with nuclei of heavy hydrogen, radiophosphorus (atomic weight 30, atomic number 15) is one of two products By writing down the transformation equation, show what the other product must be (b) Why is the term radiophosphorus used?

6  ${}_{15}\text{P}^{32}$  and protons are obtained when a certain element is bombarded with neutrons Find the atomic weight and the atomic number of this element

7 (a) Discuss as fully as you can the passage of neutrons through matter, describing the various interactions of the neutrons and atoms which may occur Where possible make specific reference to tissue (b) Write the reaction equation for one method that has been used to obtain neutrons in abundance (c) What protection would you use against a powerful source of neutrons?

8 (a) Radiophosphorus  ${}_{15}\text{P}^{32}$  is produced in the following ways, in each of which the bombarding particle is absorbed (i) sulphur (atomic number 16, mass number 32) is bombarded with neutrons, (ii) chlorine (atomic number 17, mass number 35) is bombarded with neutrons, (iii) phosphorus (atomic number 15, mass number 31) is bombarded with deuterons, (iv) silicon (atomic number 14, mass number 29) is bombarded with alpha particles Write the equations for these reactions (b) What radiation is emitted by  ${}_{15}\text{P}^{32}$ , and what is its half period?

9 (a) Explain fully how bombarding alpha particles were used in the experiment which led to the discovery of neutrons (b) Neutrons are sometimes produced by the bombardment of the lithium isotope of mass number 7 by high speed deuterons Write down the probable transformation equation (c) Explain one method of manufacturing radioactive sodium

10 Explain, with nuclear equations, (i) how neutrons are obtained by the method used in the original discovery, and (ii) by bombarding ice made from heavy water

## CHAPTER XVIII

### URANIUM FISSION AND ATOMIC PILES

#### 207 Energy from Destruction of Matter and Nuclear Fission.

-- If man could destroy matter and harness the energy released, the consequences would be amazing. Although 1 million electron-volts are equal to only  $1.6 \times 10^{-8}$  erg, the number of atoms in even a few milligrams of matter is so enormous that, if they all did disappear and change into energy, the results would be startling. If we use the relation  $E = mc^2$ , we find that for  $m = 1$  gram,  $E$  is 250 million kilowatt hours. At once it may be stated that no such disappearance of matter has been observed.

We have seen, however, that when nuclear reactions take place, sometimes there is a loss of mass associated with matter, with an equivalent release of energy. For example, the results of the bombardment of lithium by protons suggest that in this process we may have a useful release of energy. A single 0.3 mev proton brings about the release of two alpha particles, each with 8.7 mev, and this looks like a profitable business. The profit, however, is more apparent than real because, for every proton which hits a lithium atom in the right way to cause this reaction, some ten million protons are fired without making any direct hits. Since the energy expended in shooting this large number is entirely wasted, the efficiency of this reaction as a source of power is extremely low.

Still another means of obtaining energy from the disappearance of matter is provided by the phenomenon of *fission*, a type of disintegration in which a heavy nucleus, like uranium, after coalescing with a neutron, disintegrates with two particles of comparable size as its major products.

More than one country shared in the honor of the discovery of fission. In 1938, Hahn and Strassmann in Germany, following up work done by Curie and Savitch in France, found that a group of the radioactive bodies which resulted from the bombardment of uranium by neutrons were chemically similar to the element barium. They eventually concluded that barium was a product of the uranium neutron interaction. Now the formation of an element, such as barium, which occurs in the middle range of the periodic table, as a result of the union of a very heavy element like uranium with a neutron, was such a new and unexpected phenomenon that it was startling. But there was no doubt about the matter.

Later, Meitner, when working at the Physical Institute, Academy of Sciences, Stockholm, and Frisch, of the Institute of Theoretical Physics, Copenhagen, come to the conclusion that "the uranium nucleus has only small stability of form and may, after neutron capture, divide itself into two nuclei of roughly equal size. They proposed the name "fission" to describe the phenomenon and predicted that "these two nuclei will repel each other and should gain a total kinetic energy of about 200 million electron-volts" This picture of fission was soon well established.

A beautiful illustration of the phenomenon is given in Fig 208, the reproduction of a photograph taken by Professor Pierre Demers of the University



FIG 208 Enlargement showing the tracks of the two heavy fragments resulting from the fission of uranium 235 by a neutron

of Montreal This photograph shows the tracks of the two heavy fragments resulting from the fission of  $U^{235}$  and was obtained by using the photographic emulsion method The origin, where fission takes place, is marked by the short blank gap opposite the zero mark on the accompanying scale The heavy tracks on either side of the zero mark the paths of the heavy fission fragments To quote Dr Demers, "the track at the left is longer and denser than the other one which dipped out of focus It shows one bend after a collision with a nucleus, probably of silver or of bromine, which traveled some distance and left that other short dense track going up Occasional slight bending is visible at other points along the two fission tracks"

From the standpoint of the useful release of energy and possible development of power, uranium fission is of importance for two reasons (1) the large amount, approximately 200 mev, of energy released per single fission, and (2) the possibility of a chain reaction

It is not difficult to estimate the amount of energy released per fission For elements whose atomic weights are midway between those of very light elements like hydrogen and helium and the very heavy elements like radium and uranium, the mass per particle (neutron or proton) in the nucleus is less than for either the light or heavy elements A concrete example should make the point clear The exact atomic mass of uranium<sup>235</sup> is 235.12, hence the average mass per neutron or proton in the nucleus is slightly greater than 1

Now consider the element barium<sup>138</sup>. Since its atomic mass is 137.916, the average mass of its 138 neutrons and protons is slightly *less* than 1. The same may be said of lanthanum<sup>139</sup>, another element which appears as a fission product, with an atomic mass of 138.955. When, therefore, a heavy nucleus such as  $U^{235}$  gives rise on disintegration to products of intermediate weight like Ba and La, there is a loss of mass associated with matter and hence a gain of energy. Remembering the conversion relation, 0.0011 of an atomic mass unit is equal to 1 mev, the reader can show from the above numbers that approximately 200 mev are released per fission.

As already indicated, in terms of kilowatt-hours 200 mev is an extremely small amount of energy. But if a sufficiently large number of atoms undergo fission, the resultant release of energy can be very large. For example, if all the atoms in one pound of  $U^{235}$  are disintegrated in this way, the total energy released is of the order of 11 million kilowatt-hours.

**208 The Chain Reaction** — The second reason why fission is so important from the energy standpoint is due to the fact that in addition to the two heavy fragments, the products of disintegration include one or more neutrons. Thus, *fission is caused by neutrons, and neutrons are emitted in the process*. It is therefore possible that, once fission is started, these emitted neutrons, or some of them, can cause further fission, with further emission of more neutrons, thus giving a chain reaction with liberation of energy continuing as long as the disintegrating chain goes on. If the energy is liberated at an extremely rapid rate, a bomb may result, if, however, the rate is slow and controlled, there is the possibility of harnessing the energy released as a new source of power.

What, then, are the possibilities of establishing such a chain reaction, and, if established, how can it be controlled so that, once started, it does not run amok like a fire in a dry forest? The answers to these questions were provided during the years of World War II, in work of such importance that we are sometimes said to live in a new age, designated by the much abused word *atomic*. As this work has far-reaching consequences in radiology, we shall examine somewhat carefully the conditions necessary to establish a chain reaction.

We have noted above that in a single fission, from 1 to 3 neutrons are emitted. Suppose that the average number is 2 and that each liberated neutron is able to bring about further fission. It is easy to see that the total number of neutrons would rapidly increase, being 2 after the first generation, then 4 or  $2^2$ , then 8 or  $2^3$ , and so on until in a short time the number is very large. When an atomic bomb explodes, this rapid chain increase actually

takes place, but, with ordinary masses of even purified uranium there is no such chain reaction for several reasons. (1) The element uranium consists of about 99.3 per cent of  $U^{238}$ , 0.7 per cent of  $U^{235}$ , and such a small fraction of  $U^{234}$  that in our discussion it may be neglected. Now  $U^{235}$  undergoes fission much more readily than  $U^{238}$ . To be more exact, fission of  $U^{235}$  is brought about by neutrons of any speed, very slow thermal neutrons (with energy of the order of 0.025 mev) being most effective of all. On the other hand, although neutrons possessing more than 1 mev of energy cause fission in  $U^{238}$ , those with energy less than that amount do not do so. Since the average kinetic energy of neutrons liberated by fission is a little less than 1 mev, fission of  $U^{238}$  is decidedly small. (2) These fast neutrons with energy a little less than 1 mev, on striking nuclei of atoms of  $U^{238}$  bounce off losing only a little energy at each collision (because the mass of  $U^{238}$  is so much greater than that of a neutron). They, therefore, keep bouncing about, most of them making many collisions and so being gradually slowed down, until they are all accounted for by the following processes: (i) A few hit the relatively small number of  $U^{235}$  nuclei, causing fission. (ii) Some escape altogether from the mass of uranium in which they were originally generated. (iii) Some have been slowed down enough to be captured by  $U^{238}$ , without resulting fission. This capture is a very important process which takes place with a high degree of probability for neutrons with energy about 38 electron volts. (iv) If the uranium contains impurities many neutrons are captured by their atoms.

We see, therefore, that if a certain number of neutrons are present at any instant in a given mass of uranium, as time goes on there will be a gain in the number because of fission of  $U^{235}$  (2 to 3 being liberated per fission), and a loss due to escape and to capture by  $U^{238}$  and by impurities. If the losses exceed the gains, the number of neutrons will steadily decrease, and a chain reaction is not possible. Actually, none is set up in ordinary uranium. To establish a chain reaction, as is done in atomic piles, the practical problem is (a) to make the gains just exceed the losses and (b) to devise a control by means of which the process can be started or stopped.

Gains can be increased by increasing the percentage of  $U^{235}$ , that is, by enriching the pile, to use the technical phrase. With a mass of ordinary uranium, this need not be done, because by certain means immediately to be explained, it is possible both to increase the gain and decrease the loss.

Loss due to escape can be lessened by increasing the size of the mass of uranium. This is because escape of neutrons depends on the area of the surrounding surface, whereas production depends on the volume of the material. Since the area of a sphere, to take a specific example, depends on the



Now consider the element barium<sup>138</sup>. Since its atomic mass is 137.916, the average mass of its 138 neutrons and protons is slightly *less* than 1. The same may be said of lanthanum<sup>139</sup>, another element which appears as a fission product, with an atomic mass of 138.955. When, therefore, a heavy nucleus such as  $U^{235}$  gives rise on disintegration to products of intermediate weight like Ba and La, there is a loss of mass associated with matter and hence a gain of energy. Remembering the conversion relation, 0.0011 of an atomic mass unit is equal to 1 mev, the reader can show from the above numbers that approximately 200 mev are released per fission.

As already indicated, in terms of kilowatt-hours 200 mev is an extremely small amount of energy. But if a sufficiently large number of atoms undergo fission, the resultant release of energy can be very large. For example, if all the atoms in one pound of  $U^{235}$  are disintegrated in this way, the total energy released is of the order of 11 million kilowatt-hours.

**208 The Chain Reaction** — The second reason why fission is so important from the energy standpoint is due to the fact that in addition to the two heavy fragments, the products of disintegration include one or more neutrons. Thus, *fission is caused by neutrons, and neutrons are emitted in the process*. It is therefore possible that, once fission is started, these emitted neutrons, or some of them, can cause further fission, with further emission of more neutrons, thus giving a chain reaction with liberation of energy continuing as long as the disintegrating chain goes on. If the energy is liberated at an extremely rapid rate, a bomb may result, if, however, the rate is slow and controlled, there is the possibility of harnessing the energy released as a new source of power.

What, then, are the possibilities of establishing such a chain reaction, and if established, how can it be controlled so that, once started, it does not run amok like a fire in a dry forest? The answers to these questions were provided during the years of World War II, in work of such importance that we are sometimes said to live in a new age, designated by the much abused word atomic. As this work has far reaching consequences in radiology, we shall examine somewhat carefully the conditions necessary to establish a chain reaction.

We have noted above that in a single fission, from 1 to 3 neutrons are emitted. Suppose that the average number is 2 and that each liberated neutron is able to bring about further fission. It is easy to see that the total number of neutrons would rapidly increase, being 2 after the first generation then 4 or  $2^2$  then 8 or  $2^3$ , and so on until in a short time the number is very large. When an atomic bomb explodes, this rapid chain increase actually

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Loss due to escape can be lessened by increasing the size of the mass of uranium. This is because escape of neutrons depends on the area of the surrounding surface, whereas production depends on the volume of the material. Since the area of a sphere, to take a specific example, depends on the

square of its radius and its volume on the cube, it should be evident that doubling the radius will increase the surface area four times, but the volume eight times, since  $2^2 = 4$  and  $2^3 = 8$ . Consequently, as a unit is made larger and larger, escape of neutrons, depending on the surface area, becomes *relatively* less important than production, which depends on the volume. When scientists were first seeking to establish a chain reaction, one of their first problems was to estimate how large a unit would be necessary to offset the loss by escape.

Loss due to capture is decreased by purifying the uranium, removing impurities which capture neutrons.

Loss due to capture by  $U^{238}$  is reduced by slowing liberated neutrons down to thermal speeds before they (or most of them) get a chance to come in contact with atoms of this isotope. This slowing-down process has the added advantage of increasing the gain because, as we have seen, fission of  $U^{235}$  is most readily brought about by neutrons of thermal speeds.

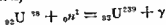
The reduction in speed is brought about by the use of what is called a *moderator*, a material consisting of *light* atoms which, when hit by fast neutrons, rapidly slows them down. (In section 197, we have already emphasized that after some twenty collisions with protons, a 5 mev neutron is slowed until its energy is only about 0.1 e.v.) For satisfactory use as a moderator, a substance must also consist of atoms which do not readily capture neutrons. Both conditions are satisfied by graphite and by heavy water.

In chain-reacting piles, therefore, masses of uranium slugs or rods are interspersed in a large mass of moderator material so that neutrons liberated in any particular slug are slowed down before they strike a neighboring one. This book is not the place to give the details of the construction of actual piles, which may be operated at power levels as low as a few watts or as high as some hundred thousand kilowatts, but our description of basic principles would not be complete without an explanation of the means of starting or stopping a pile. Control is possible because a few substances, notably cadmium and boron, absorb slow neutrons to an exceptionally high degree. Accordingly, a pile is designed so that rods or plates of a material like steel, coated with cadmium or boron, can be inserted to varying degrees inside it. Suppose a pile has been designed to operate at a certain power level with a cadmium control half way in. Then, with the rod or rods pushed all the way in, no chain reaction is possible because too many neutrons are captured by the cadmium. On gradually pulling out the rods, cadmium capture becomes less and less and at a certain stage the reaction begins. If the controls are pulled too far out, the reaction will proceed too vigorously, and care must always be exercised to guard against this.

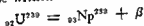
Since no special source of neutrons is placed in a chain-reacting pile, the

reader may wonder how the chain process is initiated. This is because a few stray neutrons from cosmic rays are always present in the atmosphere, and moreover, because there is always the off-chance of an odd spontaneous fission.

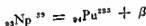
**209 Release of Nuclear Energy and Radiology** — In this book we are not concerned with the use of chain-reacting piles as possible sources of useful power. In the field of radiology, however, the controlled release of nuclear energy is of the utmost importance. To begin with, *piles are associated with colossal amounts of radioactivity*. Consider first the capture of neutrons by  $U^{238}$ , that is, the reaction



Here we have both a source of gamma radiation and the creation of the radioactive isotope  $U^{239}$ , which disintegrates with half period 23 minutes with beta emission, to form the element *neptunium*<sup>239</sup>, also radioactive. This disintegration may then be written



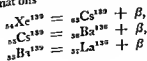
This is followed by the disintegration of  ${}_{93}Np^{239}$ , with half period 2.3 days and another beta ray emission, which leads to the manufacture of *plutonium*<sup>239</sup>, in accordance with



Although  $Pu^{239}$  is an alpha ray emitter, its half period is so long, being of the order of 200,000 years, that for many purposes it can be considered stable.

Since in a pile some capture of neutrons by  $U^{238}$  is always going on, it follows that plutonium is constantly being manufactured. It can be removed by chemical means and is of the greatest importance because, like  $U^{235}$ , it undergoes fission readily. Indeed, during the war, the primary reason huge chain-reacting piles were built was for the specific purpose of making plutonium, it being excellent fuel for atomic bombs.

A second and very important cause of the intense radioactivity associated with a pile is the fact that the products of fission are highly radioactive. Ultimately stable isotopes of elements like barium, lanthanum and many others are found, but they are the result of a series of transformations of the original fission products. For example *xenon*<sup>139</sup>, one of the many possible fission products, ultimately turns into a stable isotope of lanthanum after the following series of transformations



When, therefore, a pile is in operation, such transformations are going on constantly, with consequent intense radioactivity. In a large pile, the amount of radioactive material is the equivalent of hundreds or even thousands of grams of radium. Then, there is the constant stream of escape neutrons. As for atomic bombs, even the layman has been made well aware of the highly dangerous radiations which emanate from the place where one has been dropped.

In the important nuclear investigations which led to the chain reacting pile and to the atomic bomb, a major problem was the protection of personnel from these dangerous radiations. Through the efforts of a number of distinguished scientists, not only were workers successfully protected, but much fundamental research work relating to biological effects of radiations was carried out. It may not be amiss to quote one or two conclusions from a report on this whole problem of health protection by Dr. Robert S. Stone, the director of the group of workers whose primary concern was problems of health protection. "In a general way the opinion has been confirmed that radiation acts on tissues roughly in proportion to the specific ionization whether radiations come from outside the body or from a radioactive element inside the body. Fission products and plutonium have not been available long enough for chronic experiments to be completed, and therefore such experiments remain as a postwar project for some interested group."

Biological problems arising from the dangers of intense radiation may be classified as of a negative nature. On the positive side, chain reacting piles have created a new situation. As far as biological uses are concerned, no new fundamental principles have been discovered, but radioactive isotopes will now be available for use along the lines discussed in Chapter XVII, in hitherto undreamed of amounts. To begin with, there are the actual products of fission, such as radioactive iodine, concerning which Mayneord suggests that "it may be possible to concentrate 100 curies in 1 mm<sup>3</sup>". This, he adds, "should make an ideal beta ray emitter plaque". Then, in the pile, we have a source of neutrons for use in manufacturing useful isotopes. A good example is the manufacture of  $^{60}_{27}\text{Co}$  by the process  $^{59}_{27}\text{Co} + {}^1_0\text{n} = {}^{60}_{27}\text{Co} + \beta + \gamma$ . This may prove to be a convenient source of gamma and beta radiation.

Years of work lie ahead with untold possibilities in the biological world, for, to quote Dr. Stone again, "Nucleonics, the science of the atomic nucleus, is only in its infancy. The more it is pursued, the more chance there is of accident and the more the need therefore of a better understanding of biomedico-physical problems." To this the author of this book adds, and, on the positive side, the greater the possibility of beneficial discoveries for mankind.

## APPENDIX

### SOME USEFUL CONSTANTS AND CONVERSION FACTORS

1 coulomb	$= 3 \times 10^9$ statcoulombs
300 volts	$= 1$ statvolt
1 farad	$= 9 \times 10^{11}$ statfarads
1 microfarad	$= 9 \times 10^5$ statfarads
1 angstrom	$= 10^{-8}$ cm
1 micron	$= 10^{-4}$ mm
1 millimicron	$= 10^{-5}$ mm
1 X unit	$= 10^{-7}$ angstrom
1 electron volt	$= 1.6 \times 10^{-12}$ erg
1 electronic unit of charge	$\left\{ \begin{array}{l} = 1.60 \times 10^{-19} \text{ coulomb} \\ = 4.80 \times 10^{-10} \text{ statcoulomb} \end{array} \right.$
charge on electron	$= 1.76 \times 10^9$ coulomb per gram
mass of electron	$= 1.67 \times 10^{-24}$ gram
mass of a hydrogen atom	$= 9.11 \times 10^{-25}$ gram
mass of an electron	$= 96490$ coulomb
charge carried by 1.008 gm of hydrogen	$= 6.56 \times 10^{-17}$ erg $\times$ sec
Planck's constant ( $h$ )	$= \frac{12395}{\text{maximum voltage}}$ angstroms
shortest wave length	

TABLE XXXVI — ATOMIC NUMBERS, ATOMIC WEIGHTS AND STABLE ISOTOPES

Element	Symbol	Atomic Number	Atomic Weight	Mass Number of Isotopes
Hydrogen }	H	1	1 0081	1, 2
Deuterium }	D	1	2 014722	
Helium	He	2	4 0039	3, 4
Lithium	Li	3	6 940	6, 7
Beryllium	Be	4	9 02	9
Boron	B	5	10 82	10, 11
Carbon	C	6	12 010	12, 13
Nitrogen	N	7	14 008	14, 15
Oxygen	O	8	16 0000	16, 17, 18
Fluorine	F	9	19 00	19
Neon	Ne	10	20 183	20, 21, 22
Sodium	Na	11	22 997	23
Magnesium	Mg	12	24 32	24, 25, 26
Aluminium	Al	13	26 97	27
Silicon	Si	14	28 06	28, 29, 30
Phosphorus	P	15	30 98	31
Sulphur	S	16	32 06	32, 33, 34, 36
Chlorine	Cl	17	35 457	35, 37
Argon	A	18	39 944	36, 38, 40
Potassium	K	19	39 096	39, 40, 41
Calcium	Ca	20	40 08	40, 42, 43, 44, 46, 48
Scandium	Sc	21	45 10	45
Titanium	Ti	22	47 90	46, 47, 48, 49, 50
Vanadium	V	23	50 95	51
Chromium	Cr	24	52 01	50, 52, 53, 54
Manganese	Mn	25	54 93	55
Iron	Fe	26	55 85	54, 56, 57, 58
Cobalt	Co	27	58 94	59
Nickel	Ni	28	58 69	58, 60, 61, 62, 64
Copper	Cu	29	63 57	63, 65
Zinc	Zn	30	65 38	64, 66, 67, 68, 70
Gallium	Ga	31	69 72	69, 71
Germanium	Ge	32	72 60	70, 72, 73, 74, 76
Arsenic	As	33	74 91	75
Selenium	Se	34	78 96	74, 76, 77, 78, 80, 82
Bromine	Br	35	79 916	79, 81
Krypton	Kr	36	83 7	78, 80, 82, 84, 86
Rubidium	Rb	37	85 48	85, 87
Strontium	Sr	38	87 63	84, 86, 87, 88
Yttrium	Y	39	88 92	89
Zirconium	Zr	40	91 22	90, 91, 92, 94, 96
Molybdenum	Mo	42	95 95	92, 94, 95, 96, 97, 98, 100
Ruthenium	Ru	44	101 7	96, 98, 99, 100, 101, 102, 104
Rhodium	Rh	45	102 91	101, 103
Palladium	Pd	46	106 7	102, 104, 105, 106, 108, 110
Silver	Ag	47	107 880	107, 109
Cadmium	Cd	48	112 41	106, 108, 110, 111, 112, 113, 114, 116
Indium	In	49	114 76	113, 115

Element	Symbol	Atomic Number	Atomic Weight	Mass Number of Isotopes
Tin	Sn	50	118.70	112, 114, 115, 116, 117, 118, 119, 120, 122, 124
Antimony	Sb	51	121.76	121, 123
Tellurium	Te	52	127.61	120, 122, 123, 124, 125, 126, 128, 130
Iodine	I	53	126.92	127
Xenon	Xe	54	131.3	124, 126, 128, 129, 130, 131, 132, 134, 136
Caesium	Cs	55	132.91	133
Barium	Ba	56	137.36	130, 132, 134, 135, 136, 137, 138
Lanthanum	La	57	138.92	139
Cerium	Ce	58	140.13	136, 138, 140, 142
Praseodymium	Pr	59	140.92	141
Neodymium	Nd	60	144.27	142, 143, 144, 145, 146, 148, 150
Samarium	Sm	62	150.43	144, 147, 148, 149, 150, 152, 154
Europium	Eu	63	152.0	151, 153
Gadolinium	Gd	64	156.9	152, 154, 155, 156, 157, 158, 160
Terbium	Tb	65	159.2	159
Dysprosium	Dy	66	162.46	158, 160, 161, 162, 163, 164
Holmium	Ho	67	163.5	165
Erbium	Er	68	167.2	162, 164, 166, 167, 168, 170
Thulium	Tm	69	169.4	169
Ytterbium	Yb	70	173.5	168, 170, 171, 172, 173, 174, 176
Lutetium	Lu	71	175.0	175, 176
Hafnium	Hf	72	178.6	174, 176, 177, 178, 179, 180
Tantalum	Ta	73	180.88	181
Tungsten	W	74	183.92	180, 182, 183, 184, 186
Rhenium	Re	75	186.31	185, 187
Osmium	Os	76	190.2	184, 186, 187, 188, 189, 190, 192
Iridium	Ir	77	193.1	191, 193
Platinum	Pt	78	195.23	192, 194, 195, 196, 198
Gold	Au	79	197.2	197
Mercury	Hg	80	200.61	196, 198, 199, 200, 201, 202, 204
Thallium	Tl	81	204.39	203, 205
Lead	Pb	82	207.21	204, 206, 207, 208
Bismuth	Bi	83	209.00	209



TABLE XXXVI—ATOMIC NUMBERS, ATOMIC WEIGHTS AND STABLE ISOTOPES

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Beryllium	Be	4	9.02	9
Boron	B	5	10.82	10, 11
Carbon	C	6	12.010	12, 13
Nitrogen	N	7	14.008	14, 15
Oxygen	O	8	16.0000	16, 17, 18
Fluorine	F	9	19.00	19
Neon	Ne	10	20.183	20, 21, 22
Sodium	Na	11	22.997	23
Magnesium	Mg	12	24.32	24, 25, 26
Aluminum	Al	13	26.97	27
Silicon	Si	14	28.06	28, 29, 30
Phosphorus	P	15	30.98	31
Sulphur	S	16	32.06	32, 33, 34, 36
Chlorine	Cl	17	35.457	35, 37
Argon	Ar	18	39.944	36, 38, 40
Potassium	K	19	39.096	39, 40, 41
Calcium	Ca	20	40.08	40, 42, 43, 44, 46, 48
Scandium	Sc	21	45.10	45
Titanium	Ti	22	47.90	46, 47, 48, 49, 50
Vanadium	V	23	50.95	51
Chromium	Cr	24	52.01	50, 52, 53, 54
Manganese	Mn	25	54.93	55
Iron	Fe	26	55.85	54, 56, 57, 58
Cobalt	Co	27	58.94	59
Nickel	Ni	28	58.69	58, 60, 61, 62, 64
Copper	Cu	29	63.57	63, 65
Zinc	Zn	30	65.38	64, 66, 67, 68, 70
Gallium	Ga	31	69.72	69, 71
Germanium	Ge	32	72.60	70, 72, 73, 74, 76
Arsenic	As	33	74.91	75
Selenium	Se	34	78.96	74, 76, 77, 78, 80, 82
Bromine	Br	35	79.916	79, 81
Krypton	Kr	36	83.7	78, 80, 82, 84, 86
Rubidium	Rb	37	85.48	85, 87
Strontium	Sr	38	87.63	84, 86, 87, 88
Yttrium	Y	39	88.92	89
Zirconium	Zr	40	91.22	90, 91, 92, 94, 96
Molybdenum	Mo	42	95.95	92, 94, 95, 96, 97, 98, 100
Ruthenium	Ru	44	101.7	96, 98, 99, 100, 101, 102, 104
Rhodium	Rh	45	102.91	101, 103
Palladium	Pd	46	106.7	102, 104, 105, 106, 108, 110
Silver	Ag	47	107.880	107, 109
Cadmium	Cd	48	112.41	106, 108, 110, 111, 112, 113, 114, 116
Indium	In	49	114.76	113, 115

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Iodine	I	53	126.92	127
Xenon	Xe	54	131.3	124, 126, 128, 129, 130, 131, 132, 134, 136
Caesium	Cs	55	132.91	133
Barium	Ba	56	137.36	130, 132, 134, 135, 136, 137, 138
Lanthanum	La	57	138.92	139
Cerium	Ce	58	140.13	136, 138, 140, 142
Praseodymium	Pr	59	140.92	141
Neodymium	Nd	60	144.27	142, 143, 144, 145, 146, 148, 150
Samarium	Sm	62	150.43	144, 147, 148, 149, 150, 152, 154
Europium	Eu	63	152.0	151, 153
Gadolinium	Gd	64	156.9	152, 154, 155, 156, 157, 158, 160
Terbium	Tb	65	159.2	159
Dysprosium	Dy	66	162.46	158, 160, 161, 162, 163, 164
Holmium	Ho	67	163.5	165
Erbium	Er	68	167.2	162, 164, 166, 167, 168, 170
Thulium	Tm	69	169.4	169
Ytterbium	Yb	70	173.5	168, 170, 171, 172, 173, 174, 176
Lutecium	Lu	71	175.0	175, 176
Hafnium	Hf	72	178.6	174, 176, 177, 178, 179, 180
Tantalum	Ta	73	180.88	181
Tungsten	W	74	183.92	180, 182, 183, 184, 186
Rhenium	Re	75	186.31	185, 187
Osmium	Os	76	190.2	184, 186, 187, 188, 189, 190, 192
Iridium	Ir	77	193.1	191, 193
Platinum	Pt	78	195.23	192, 194, 195, 196, 198
Gold	Au	79	197.2	197
Mercury	Hg	80	200.61	196, 198, 199, 200, 201, 202, 204
Thallium	Tl	81	204.39	203, 205
Lead	Pb	82	207.21	204, 206, 207, 208
Bismuth	Bi	83	209.00	209

## INTERNATIONAL RECOMMENDATIONS FOR X-RAY AND RADIUM PROTECTION\*

Revised by the International X Ray and Radium Protection Commission at the Fifth International Congress of Radiology, Chicago, September, 1937

### International Recommendations

1 The dangers of overexposure to x rays and radium can be avoided by the provision of adequate protection and suitable working conditions. It is the duty of those in charge of x ray and radium departments to insure such conditions for their personnel. The known effects to be guarded against are

- (a) Injuries to the superficial tissues,
- (b) Changes in the blood and derangements of internal organs, particularly the generative organs

The evidence at present available appears to suggest that under satisfactory working conditions a person in normal health can tolerate exposure to x rays or radium gamma rays to an extent of about 0.2 international roentgen ( $r$ ) per day, or  $1r$  per week. On the basis of continuous irradiation during a working day of seven hours, this figure corresponds to a tolerance dosage rate of  $10^{-5}r$  per second. The protective values given in these recommendations are generally in harmony with this figure under average conditions.

#### I WORKING HOURS, ETC

2 The following working hours, etc., are recommended for whole time x ray and radium workers

- (a) Not more than seven working hours a day in temperate or cold climates. For workers in tropical climates, shorter hours may be desirable.
- (b) Not more than five working days a week, the off days to be spent as much as possible out of doors.
- (c) Not less than four weeks holiday a year, preferably consecutively.
- (d) Whole time workers in hospital x ray and radium departments should not be called upon for other hospital service.
- (e) X ray, and particularly radium workers should be systematically submitted, both on entry and subsequently at least twice a year, to expert medical, general, and blood examinations, special attention being paid to the hands. These examinations will determine the acceptance, refusal, limitation, or termination of such occupation.
- (f) The amount of radiation received by operators should be systematically checked to insure that the tolerance dose is not exceeded. For this purpose, photographic films or small capacity condensers may be carried on the person.

#### II GENERAL X RAY AND RADIUM RECOMMENDATIONS

- 3 X-ray departments should not be situated below ground floor level.
- 4 All rooms, including dark rooms, should be provided with windows affording good natural lighting and ready facilities for admitting sunshine and fresh air when ever possible.

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5 All rooms should be provided with adequate exhaust ventilation. In certain climates it may be necessary to have recourse to air conditioning. For rooms of normal dimensions, say 3,000 cubic feet (90 c meters) in which corona free apparatus is installed, the ventilating system should be capable of renewing the air of the room not less than six times per hour, while up to ten times may be required when the apparatus is not corona free. Large rooms require proportionately fewer changes of air per hour than small ones. Air inlets and outlets should be arranged to afford cross wise ventilation of the room.

6 All rooms should preferably be decorated in light colors.

7 A working temperature of about 18°-22°C. (65°-72°F) is desirable in x ray rooms.

8 X ray rooms should be large enough to permit a convenient layout of the equipment. A minimum floor area of 250 sq ft (23 sq meters) is recommended for x ray rooms, and 100 sq ft (10 sq meters) for dark rooms. Ceilings should be not less than 11 ft (3.5 meters) high.

9 High tension generators employing mechanical rectification should preferably be placed in a separate room from the x ray tube.

### III X RAY PROTECTIVE RECOMMENDATIONS

10 An x ray operator should on no account expose himself to a direct beam of x rays.

11 An operator should place himself as remote as practicable from the x ray tube. It should be borne in mind that valve tubes are capable of producing x rays.

12 The x ray tube should be self protected, or otherwise surrounded as completely as possible, with protective material of adequate lead equivalent.\*

13 The following lead equivalents are recommended under average conditions.

X rays Generated by Peak Voltages	Minimum Equivalent Thickness of Lead
Not exceeding 75 kv	1 mm
100	1.5
125	2
150	2.5
175	3
200	4
250	6
300	9
350	12
400	15
(600)	(35)

(A) *Diagnostic Work* — 14 In the case of diagnostic work with other than completely protected tubes the operator should be afforded additional protection from stray radiation by a screen of a minimum lead equivalent of one millimeter.

15 Screening examinations should be conducted as rapidly as possible with minimum intensities and apertures, particularly when fractures are reduced under x rays. Palpitation with the hand should be reduced to the minimum.

\* The lead equivalent of a given thickness of protective material is that thickness of lead which is equally opaque to x rays excited at some specified peak voltage.

16 The lead glass of fluorescent screens should have the protective values recommended in paragraph 13

17 In the case of screening stands, the fluorescent screen should, if necessary, be provided with a protective "surround," so that adequate protection against direct radiation is afforded for all positions of the screen and diaphragm

18 Screening stands and couches should provide adequate arrangements for protecting the operator against scattered radiation from the patient

19 Protective gloves, which should be suitably lined with fabric or other material, should have a protective value not less than one third millimeter lead throughout both back and front (including fingers and wrist) Protective aprons should have a minimum lead value of one half millimeter

(B) *Treatment* — 20 In the case of x ray treatment, the operator is best stationed completely outside the x ray room behind a protective wall, the lead equivalent of which will depend on the circumstances In the case of a single x ray tube excited by voltages up to 200 kv, the protective wall should have a minimum lead equivalent of two millimeters This figure should be increased in the case of higher exciting voltages or of heavy tube currents or if the protective value of the x ray tube enclosure falls short of the value given in paragraph 13 In such event the remaining walls, floor, and ceiling may also be required to provide supplementary protection for adjacent occupants to an extent depending on the circumstances Full protection should be provided in all those directions in which the direct beam can operate

Inspection windows in screens and walls should have protective lead values equivalent to that of the surrounding screen or wall

21 In those cases in which an x ray tube is continuously excited and treatment periods are regulated by means of a shutter, some form of remote control should be provided for the shutter, to insure that the operator is not exposed to direct radiation while manipulating the shutter or filter

22 Efficient safeguards should be adopted to avoid the omission of a metal filter in x ray treatment, for example, by an interlocking device or by continuously measuring the emergent radiation Protective screens and applicators (cones) used in treatment to define the ports of entry of x ray beams should be sufficiently thick to reduce the dosage rate outside the direct field of irradiation to less than  $10^{-5}$  roentgen per second

#### IV. ELECTRICAL PRECAUTIONS IN X RAY ROOMS

23 The floor covering of the x ray rooms should be insulating material such as wood, rubber, or linoleum

24 Where permanent overhead conductors are employed, they should be not less than 9 feet (3 meters) from the floor They should consist of stout metal tubing or other coronaless type of conductor The associated connecting leads should be of coronaless wire kept taut by suitable rheophores

25 Wherever possible, earthed guards or earthed sheaths should be provided to shield the more adjacent parts of the high tension system Unshielded leads to the x ray tube should be in positions as remote as possible from the operator and the patient The use of "shockproof" x ray equipment, in which the high tension circuit is completely enclosed in earthed conductors, is recommended In all cases, however, indiscriminate handling of x ray tubes during operation should be forbidden Unless there are reasons to the contrary, metal parts of the apparatus and room should be efficiently earthed

26 Main and supply switches should be very accessible and distinctly indicated. They should not be in the proximity of the high tension system, nor should it be possible for them to close accidentally. The use of quick acting, double pole circuit breakers is recommended. Overpowered fuses should not be used. If more than one apparatus is operated from a common generator, suitable high tension, multiway switches should be provided. In the case of some of the constant potential generators, a residual charge is held by the condensers after shutting down, and a suitable discharging device should, therefore, be fitted. Illuminated warning devices which operate when the equipment is "alive" serve a useful purpose. The staff should be trained in the use of first aid instructions dealing with electrical shock. If foot switches are used they should be connected in series with an ordinary switch, and should be so designed that they cannot be locked to keep the circuit "alive" and are not capable of being closed accidentally.

27 Some suitable form of kilovoltmeter should be provided to afford a measure of the voltage operating the x ray tube.

28 Low flashpoint anesthetics should never be used in conjunction with x rays.

#### V. FILM STORAGE PRECAUTIONS

29 The use of noninflammable x-ray films is strongly recommended. In the case of inflammable films, suitable precautions should be taken as regards their use and storage. Large stocks should be kept in isolated stores, preferably in a separate building or on the roof.

#### VI RADIUM PROTECTIVE RECOMMENDATIONS

(A) *Radium Salts* — 30 Protection for radium workers is required from the effects of

(a) Beta rays upon the hands,

(b) Gamma rays upon the internal organs, vascular and reproductive systems.

31 In order to protect the hands from beta rays, reliance should be placed, in the first place, on distance. The radium should be manipulated with long handled forceps and should be carried from place to place in long handled boxes, lined on all sides with at least one centimeter of lead. All manipulations should be carried out as rapidly as possible.

32 Radium, when not in use, should be stored in a safe as distant as possible from the personnel. It is recommended that the safe should be provided with a number of separate drawers individually protected. The amount of protection should correspond to the values given in the following table. These values, which are based on working conditions where there is proximity to radium may be reduced for larger working distances.

Maximum Quantity of Radium Element	Thickness of Lead
0.05 gm	5 cm
0.2	8.5
0.5	10
1.0	11.5
2.0	13
5.0	15
10.0	17

33 A separate room should be provided for the "make-up" of screened tubes and applicators, and this room should be occupied only during such work

34 In order to protect the body from the penetrating gamma rays during the handling of radium, a screen of not less than 2.5 centimeters of lead should be used, and proximity to the radium should occur only during actual work, and for as short a time as possible

35 The measurement room should be a separate room, and it should preferably contain the radium only during its actual measurement

36 Nurses and attendants should not remain in the same room as patients undergoing radium treatment with quantities exceeding one half gram

37 All unskilled work, or work which can be learned in a short period of time, should preferably be carried out by temporary workers, who should be engaged on such work for periods not exceeding six months. This applies especially to nurses and those engaged in "making up" applicators

38 Radium containers should be tested periodically for leakage of radon. Prejudicial quantities of radon may otherwise accumulate in radium safes, etc., containing a number of leaky containers

39 Discretion should be exercised in transmitting radium salts by post. In the case of small quantities (less than 10 mg. of radium element) it is recommended that the container should be lined throughout with lead not less than three millimeters thick, while for quantities between 10 and 50 mg. of radium element, the lead container should be supported in the center of a box with a minimum dimension of 30 cm. Packages containing more than 50 mg. of radium element are preferably sent by rail or hand under suitable conditions of protection

(B) *Radon* — 40 In the manipulation of radon, protection against beta and gamma rays is required, and automatic or remote controls are desirable

41 The handling of radon should be carried out, as far as possible, during its relatively inactive state

42 Precautions should be taken against excessive gas pressures in radon plants. The escape of radon should be very carefully guarded against, and the room in which it is prepared should be provided with an exhaust fan controlled from outside the room

43 Where radon is likely to come in direct contact with the fingers, thin rubber gloves should be worn to avoid contamination of the hands with active deposit. Otherwise, the protective measures recommended for radium salts should be carried out

44 The pumping room should preferably be contained in a separate building. The room should be provided with a connecting tube from the special room in which the radium is stored in solution. The radium in solution should be heavily screened to protect people working in adjacent rooms. This is preferably done by placing the radium solution in a lead lined box, the thickness of lead recommended being according to the table in paragraph 32

(C) *Radium beam Therapy* — 45 The risks to the operator attendant on the use of large quantities of radium in radium beam therapy may be largely obviated if some system of remote control is adopted by which the radium is only introduced into the "bomb" after the latter has been adjusted in position on the patient. If such arrangements are not available, the importance of expeditious handling is stressed

46 Rooms used for radium-beam therapy should provide adequate protection for adjacent wards and rooms in permanent occupation

The following minimum lead thicknesses are required to secure a tolerance dosage

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